PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : G21B 1/00

A1

(11) International Publication Number: WO 96/36969

(43) International Publication Date: 21 November 1996 (21.11.96)

(21) International Application Number: PCT/GB96/01187

(22) International Filing Date: 17 May 1996 (17.05.96)

(30) Priority Data:
9509982.6 17 May 1995 (17.05.95) GB

(71)(72) Applicant and Inventor: BROWNE, Peter, Finlay [GB/GB]; 11 Davenfield Road, Didsbury, Manchester M20 6TL (GB).

(74) Agent: ATKINSON, Peter, Birch; Marks & Clerk, Sussex House, 83-85 Mosley Street, Manchester M2 3LG (GB).

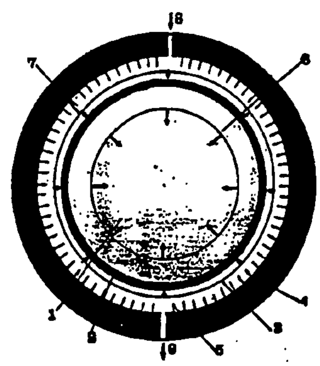
(81) Designated States: AL, AM, AT, AU, AZ, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IS, JP, KE, KG, KP, KR, KZ, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, US, UZ, VN, ARIPO patent (KE, LS, MW, SD, SZ, UG), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

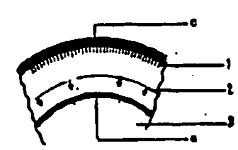
Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

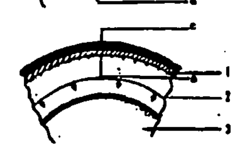
(54) Title: TOWARD A SHOCK-WAVE FUSION REACTOR

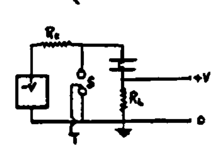
(57) Abstract

Apparatus for generating nuclear power comprises (i) a solid or liquid medium in which a converging shock wave will propagate towards a focus, (ii) shock wave generation means for launching a converging shock wave into said medium so that the shock wave converges towards the focus, and (iii) fusion fuel either distributed within the converging medium or confined to a focal cavity in said medium. The converging medium is such as to be capable of reducing the volume of a shock wave wholly by convergence of the shock wave towards a focus so that the energy per particle in the converged shock wave exceeds the threshold value for effecting fusion in said fuel.









FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AM	Armenia	GB	United Kingdom	MW	Malawi
AT	Austria	GE	Georgia	MX	Mexico
AU	Australia	GN	Guinea	NE	Niger
BB	Barbados	GR	Greece	NL	Netherlands
BE	Belgium	HU	Hungary	NO	Norway
BF	Burkina Faso	IE	Ireland	NZ	New Zealand
BG	Bulgaria	IT	Italy	PL	Poland
BJ	Benin	JP	Japan	PT	Portugal
BR	Brazil	KE	Kenya	RO	Romania
BY	Belarus	KG	Kyrgystan	RU	Russian Federation
CA	Canada	KP	Democratic People's Republic of Korea	SD	Sudan
CF	Central African Republic			SE	Sweden
CG	Congo	KR	Republic of Korea	SG	Singapore
CH	Switzerland	KZ	Kazakhstan	SI	Slovenia
CI	Côte d'Ivoire	LI	Liechtenstein	SK	Slovakia
CM	Cameroon	LK	Sri Lanka	SN	Senegal
CN	China	LR	Liberia	SZ	Swaziland
CS	Czechoslovakia	LT	Lithuania	TD	Chad
CZ	Czech Republic	LU	Luxembourg	TG	Togo
DE	Germany	LV	Latvia	TJ	Tajikistan
DK	Denmark	MC	Monaco	TT	Trinidad and Tobago
EE	Estonia	MD	Republic of Moldova	UA	Ukraine
ES	Spain	MG	Madagascar	UG	Uganda
FI	Finland	ML	Mali	US	United States of America
FR	France	MN	Mongolia	UZ	Uzbekistan
GA	Gabon	MR	Mauritania	VN	Viet Nam

TOWARD A SHOCK-WAVE FUSION REACTOR

P. F. Browne

(Addenda completed 26th March, 1966, to patent application "Shock Wave Fusion Reactor", No. 9509982.6, priority date 17 May, 1995).

1. Technical Field and Background

The invention relates to generation of energy by fusion of light atomic nuclei to form a product nucleus with liberation of energy of order megaelectron volts (Mev) per fusion as compared to tens of electron volts per chemical reaction in fossil fuels.

The "fusion fuel" most commonly contemplated is hydrogen in the form of its heavy isotopes deuterium (D) and tritium (T). Preferred, although not the only, reactions are:

$$^{2}D + {}^{2}D \rightarrow \begin{cases} {}^{3}He(0.82\ Mev) + {}^{1}n(2.45\ Mev) \\ {}^{3}T(1.01\ Mev) + {}^{1}H(3.02\ Mev) \end{cases} \qquad (1)$$

$$^{2}D + {}^{3}T \rightarrow {}^{4}He(3.5\ Mev) + {}^{1}n(14.1\ Mev) \qquad (2)$$

where standard scientific notation is used, the energies in brackets being those of the particular reaction products. Reactions (1) are referred to as DD fusion, and reaction (2) as DT fusion. The two DD reactions occur with about equal probabilities.

The total energy released per DD fusion (an average of both branches) is 3.6 Mev, and the energy released per DT fusion is 17.6 Mev.

For the same energy of bombarding deuteron and for the same number of target nuclei (D or T) per unit volume, the probability per unit time for a DT reaction exceeds that for a DD reaction by a factor of order 100.

In order for a fusion to occur the fusing nuclei must

approach each other more closely than a critical distance, which is difficult to arrange because of the electrostatic repulsion of the charges of the nuclei. This leads to threshold value of the kinetic energies of the nuclei before fusion, which implies a threshold temperature if the particle motions are randomized. Conventional approaches to the realization of a fusion reactor have, as yet, not been able to provide a sufficient density of ions above the temperature threshold for a sufficient length of time.

WO-A-91/13531 discloses apparatus for effecting a fusion reaction comprising

a spherical energy store itself comprised of a stressed metal or metal allow in which the stress has been induced at a plurality of discrete regions by atoms or ions at interstitial sites of the lattice, the energy stored in the lattice being capable of at least partial release when a shock wavefront passes over said stressed regions,

means for stimulating release of strain potential energy in the form of shock waves, and

a fusion fuel element positioned so that a fusion reaction is initiated by the shock waves.

In operation of the apparatus disclosed in WO-A-91/13531, a spherically symmetric trigger shock front is directed to the energy store. This shock front results in localised readjustment of the lattice strain required to release strain potential energy. The released strain potential energy takes the form of secondary shock waves (emanating from localized regions of stress which mutually interfere to provide a resultant shock wave with the same shape as the trigger shock wave which is thereby amplified coherently. The overall result is that a considerably amplified shock front is produced which is capable to effect fusion in the fuel.

There is however a disadvantage associated with the

proposal of WO-A-91/13531 in that the energy store repetitively required replacement (since the strain energy is released).

It is therefore an object of the present invention to obviate or mitigate the above-mentioned disadvantage.

According to a first aspect of the present invention there is provided apparatus for generating nuclear power comprising

(i) a solid or liquid medium, herein referred to as a converging medium, in which a converging shock wave will propagate toward a focus,

(ii) shock wave generation means for launching a converging shock wave into said medium so that the shock wave converges toward the focus, and

(iii) fusion fuel either distributed within the converging medium or confined to a focal cavity in said medium,

the converging medium being such as to be capable of reducing the volume of a shock wave wholly by convergence of the shock wave toward a focus so that the energy per particle in the converged shock wave exceeds the threshold value for effecting fusion in said fuel.

The volume of a shock wave is the product of surface area of the wavefront and thickness.

The term "energy per particle" refers to energy per particle of the medium in which the shock wave propagates. The wave is a disturbance which passes through the medium. At any time certain atoms of the medium are disturbed by the wave, and these atoms have increased energy - much increased energy when the shock wave concentrates its energy as it approaches a focus.

wave concentrates its energy as it approaches a focus. The particles are particles of the medium, and they include all particles of the medium which convey the disturbance at any particular time (i.e. all particles in the disturbed region of the medium). Fusion fuel particles may or may not be among these particles.

Therefore in the apparatus of the invention, the final energy per particle is attained from an initial energy per particle typical of conventional shock generators and the apparatus can operate repetitively by means of convergence of the shock wave front alone thereby avoiding the need to amplify the shock wave front by the mechanism of WO-A-91/13531 which had the disadvantage of being non-repetitive.

Subject to plausible assumptions, the energy per particle in a converging shock wave increases as the inverse square of the radius of the shock wavefront, so that after convergence from initial radius r_0 to final radius r_f the energy per particle will have increased by a factor $(r_0 / r_f)^2$, and if the energy per particle in the shock wave initially (at launch) is for example 0.1 ev and the convergence ratio is $r_0 / r_f = 300$ then the final energy will be ≈ 10 kev which is the preferred minimum for initiating a useful rate of fusion reactions.

Preferably the final energy per particle is at least 15 kev, or preferably at least 20 kev.

Preferably the convergence ratio r_0 / r_f achieved in the apparatus of the invention is at least 100. more preferably at least 150, most preferably at least 300.

It will be appreciated that the energy for effecting the fusion reaction is, in effect, provided by two steps. In the first step a shock wave of large volume is generated to give as much initial energy per particle as possible. In the second step, the shock wave is converged so as to reduce its volume whereby the same energy is distributed among a smaller number of particles whereby

the energy per particle is increased. The convergence is such that the energy per particle exceeds the threshold value for a useful rate of fusion in the fuel.

2. Summary of Preferred Embodiment

A preferred apparatus according to the present invention utilises

(1) shock waves, hereafter termed "converging shock waves", whose wavefronts converge toward a focus, so that wavefront area decreases by a substantial factor during convergence,

(2) a solid or liquid medium, or a composite of more than one such medium, hereafter termed "converging medium", in which the shock waves propagate toward a focus, whether or not the focus is actually reached,

(3) means of launching repetitively converging shock waves into the converging medium,

(4) as an optional feature, a cavity in the converging medium whose boundary surface is encountered by a converging shock wave before the focus is reached.

(5) nuclei capable of undergoing exothermic fusion reactions, hereafter termed "fusion fuel", the said fusion fuel being either distributed throughout the converging medium or concentrated into a volume toward which the shock waves converge,

Provision of the above features introduces options among which are the following. Options may be chosen in

any combination.

Feature 1

With regard to feature (1), common examples of converging shock waves have a spherical shockfront which converges to a point focus, or a cylindrical shockfront which converges to a line focus. Less common exmamples create converging shock waves by reflection at a boundary surface between two media, examples being reflection of a plane shock wave by a conical or wedge-shaped boundary surface, reflection of a plane shock wave by a paraboloid shaped boundary surface toward a point focus, conversion of a shock wave which diverges from one focus of an ellipsoid into a shock wave which converges toward the other focus of the ellipsoid by reflection at the boundary surface of the ellipsoid. Plane shock waves can also be made to converge by propagation in a medium of non-uniform density, the variation with position of propagation velocity, creating a lense effect.

Feature 2

With regard to feature (2) a converging medium may be a composite of several media in contact with each other, so that the shock wave passes across boundary surfaces between media with some degree of reflection which can be minimized or adjusted to a desired value.

Feature 3

With regard to feature (3) a converging shock wave can be launched by impulsive pressure applied over the outer surface of the converging medium. Two preferred methods for providing simultaneous (or appropriately timed) impulsive pressure over a large surface area are, (i) by detonation waves in fluid (gaseous or liquid) explosive (Fig. 2a), and (ii) by mechanical impact (Fig. 2b). Apparatus for applying impulsive pressure to the surface

of a converging medium must do so repetitively. If chemical explosive is used, then gaseous or liquid form of explosive is required for rapid renewal. In more detail, these methods are as follows:

(i) Production of Detonation Wavefronts of Large Area and Controlled Shape.

A preferred method for launching a shock wave is to apply pressure by a detonation wave with the same shape of wavefront as the shockwave to be launched, the detonation wave being generated in gaseous or liquid chemical explosive in a combustion chamber surrounding the converging medium (Fig. 1a). If the converging medium is spherical, a spherical shock wave is launched by impact of a converging spherical detonation wave on the surface of the converging medium.

Creation of a detonation wave of large wavefront area and given geometry requires precise timing of the ignition (triggering) of different volume elements of the chemical explosive. The method for achieving this timing shown in Fig. 1a is to initiate a corona-type discharge at the tips of an array of pins protruding from one of two electrodes in the region where the explosive fuel is ignited ("combustion chamber"). The two electrodes are the concentric spherical walls of the combustion chamber in the example depicted in Fig. 1a. The pins are uniformly spaced (separation perhaps 5 mm) and of uniform length (perhaps 5 mm) for launching a spherical detonation wave of radius say 1 m. The smaller the separation and lengths of the pins, the shorter will be the distance propagated by the detonation wavefront before it acquires the desired uniform shape. The ignition of the explosive fluid occurs at the tips of the pins because a high electric field at the instant of application of a high voltage pulse (perhaps in the range 10 - 50 kV) between the electrodes initiates an

electrical discharge at the tips of the pins. The term "corona-discharge" often is reserved for one electrical polarity of the pins, but here either polarity can be employed. The ignition of explosive fluid in the localities of different pins should be simultaneous to within about 1 microsecond, unless timing delays are purposely introduced into the electrical feeds to the pins in order to control the shape or direction of the detonation wave. The pins may be fed through individual resistors, or through a common resistive medium.

A variant of the mechanism for launching a detonation wave of large wavefront area and desired shape is to replaces the pins by a wire mesh (or other perforated conductor) in contact with a slab of dielectric medium whose other surface is in contact with one electrode (the outer wall in the example of Fig. 1b). Mylar is a possible dielectric material; electrically glass is suitable, but lack of robustness to the explosion may exclude glass. The high voltage pulse now is applied between the conducting sheets on either side of the dielectric layer, so that the dielectric polarizes. Neutralization of induced charges within the meshes on the mesh side of the dielectric occurs by microdischarges over the surface of the dielectric, thus igniting explosive fluid locally.

(ii) Generation of Shock Waves by Mechanical Impact

A second method for launching a shock wave is to apply direct mechanical impact on the surface of the converging medium by solid projectiles, or pistons, which have been accelerated by explosive charges. A "hammer" driven by a single spherical detonation wave is shown in Fig. 1. By means of interleaving layers the effective surface area of the hammer head is able to decrease with decreasing radius.

In Fig. 2b an alternative method for delivering

mechanical impacts uniformly and simultaneously over the surface of a converging medium is depicted. Now independently accelerated projectiles are directed along radial cyclinders or "gun barrels" toward the surface of the converging medium. Acceleration may be by explosive charges introduced into each cylinder head and independently triggered, much like a multi-cylinder internal combustion engine. In this system there is the possibility of timing the independently delivered mechanical impacts in response to a feed-back signal. Acceleration of the projectiles in the radial gun barrels may be by other methods.

The facility to launch a pair of shock wavefronts in rapid succession is desirable in certain circumstances. Fig. 2d depicts a projectile which delivers double-impacts whose relative strengths and time separations are controllable.

Mechanical impacts combine high impulse strength with relatively low pressure because of the suddenness of the applied pressure. In every other respect the explosive detonation waves are preferred.

Feature 4

With regard to feature (4), there is provided the option of

I. a continuous solid or liquid converging medium

or

II. a cavity in the converging medium toward which the shock waves converge, and at the boundary of which the converged shock waves are reflected.

Options I and II created by feature 4 lead to different types of shock wave reactor, termed respectively "uniform medium reactors" (UMRs), and "focal cavity reactors"

threshold conditions for useful fusion may be easier for the FCR reactor, the additional complexity of this system may be necessary.

The essential principle of operation of either type of reactor is conversion of energy in a shockwave of large volume into energy in a shock wave of small volume without unacceptable loss of energy. Then energy distributed among a large number of particles becomes concentrated into energy in a small number of particles. This energy may be either kinetic energy or potential energy due to elastic compression, the one form of energy being convertable into the other provided that potential energy is not lost to a reflected wave.

Distinctions between the UMR and FCR variants of the reactor are clarified by the following more specific descriptions:

I. Uniform Medium Reactors (UMRs)

In "uniform medium reactors" (UMRs) fusion conditions are attained in localized volumes of the medium, of which the following are three types:

(A) a small volume surrounding the focus toward which the shock waves converge, termed "focal volume" (Fig. 3a);

(B) the volume of overlap of colliding shockfronts of the same shape and with opposite directions of propagation, so that at one instant of time the shockfronts are superimposed in their entirety (Fig. 3b);

(C) the volume of overlap of colliding shockfronts with general shape and general direction of propagation which intersect along a curve (providing a tubular volume of intersection)

which moves as the shock fronts propagate (Fig. 3c), causing the phenomenon of "jetting".

A preferred example of case (B) occurs when a spherical shock wave converging toward a focus meets, at a position close to the focus, a spherical shock wave diverging from the same focus (Fig. 3b). The diverging shock wave may be produced by reflection of a forerunning converging shock wave. Reflection near the focus may be natural or contrived, natural reflection being automatic and contrived reflection being that due to introduction of a dense core medium, for example a ball bearing (which would require support in a liquid core). The very steep pressure gradient at the front of a strong (converged) shock wave implies very sudden onset of thermalization which should eliminate radiative cooling during the inertial confinement time.

A preferred example of case (C) occurs when converging medium comprises two spherical caps on a common circular base, which is what remains of a sphere after removal of an equatorial slab from the sphere and closure of the gap so created. If the removed slab has thickness z, then spherical shock waves in the spherical caps converge toward different foci a distance z apart. Spherical shockfronts converging in the spherical caps intersect in a circular ring on the equatorial plane, this ring decreasing in radius as the shock waves converge toward their respective foci F_1 and F_2 in Fig. 3c. Particles in the collision ring are forced radially inward to form a sheet jet whose area reduces with

RECTIFIED SHEET (RULE 91)
ISA/EP

convergence of the shockfronts until the sheet collapses to the center.

The simplest case of "jetting" occurs during collision of plane shock waves propagating in directions which make angle $180^{\circ} - \alpha$ with each other. The curve of intersection now is a straight line which moves in the plane which bisects the wedge formed by the shockfront planes. The velocity of the motion is $D \operatorname{cosec} \alpha/2$, where D is propagation velocity of the shockfronts and α is the wedge angle. This velocity exceeds D by a factor of 10 for $\alpha = 11^{\circ}24'$.

It will be noted that all three fusion regions have similar volumes. In case A the focal volume V_f and radius r_f are related by $V_f = 4\pi r_f^3/3$, so that $r_f = 0.3$ cm implies $V_f = 0.11$ cm^3. In case B the shell collision volume V_s is related to shell radius r_s and shell thickness λ by $V_s = 4\pi r_s^2\lambda$, so that $r_s = 1$ cm and $\lambda = 1$ mm implies $V_s = 1.26$ cm^3. In case C tubular collision volume V_t is related to tube radius r_t and to tube length $2\pi a$ (for a ring tube of radius a) by $V_t = \pi r_t^2(2\pi a)$ so that $r_t = 1$ mm and $a = 1$ cm leads to $V_t = 0.2$ cm^3. Thus, in each case the energy of the shock wave is being shared among comparable numbers of particles.

Means of launching toward the same focus spherical shock waves which are closely separated in distance or time are shown in Fig. 2c and Fig. 2d.

II. Focal Cavity Reactors (FCRs)

In the case of FCRs fusion conditions are achieved within the focal cavity after medium material has been injected into the cavity ("off-loaded") during reflection

of the converged shockwaves. Off-loaded material is used in two ways which require different shapes of focal cavity:

(A) If the cavity boundary has the same shape as the converging shockfront, for example a spherical boundary concentric with the converging shockfront (Fig. 4a), then at reflection a dense spherical shell of medium is off-loaded with velocity twice the velocity of particles carrying the wavefront in the medium. This off-loaded shell is an ideal driver for imploding fusion material frozen to the inside wall of a capsule which is in contact with the converging medium, so that both wall material and fusion fuel are driven toward the center of the cavity where the fusion fuel reaches very high density and temperature.

(B) If the cavity boundary has shape different to that of the converging shock wave, then the shock wave meets different portions of the boundary at different times. For example, if the cavity has bi-conical shape (that of a pair of oppositely directed right circular cones on a common base - Fig. 4b) then injected particles will form a pair of oppositely directed jets which collide at the center of the cavity. If the cavity has multi-conical shape (circular cones projecting from a spherical surface in mutually orthogonal directions - Fig. 4c), then there are three pairs of opposite jets along three mutually orthogonal directions, which is six jets directed toward the center of the cavity.

Feature 5

With regard to feature (5), there is provided the option of

(i) fusion fuel distributed uniformly throughout the converging medium,

or

(ii) fusion fuel (possibly encapsulated) concentrated into a cavity within the converging medium toward which the shock waves converge.

With regard to option (i), a preferred converging medium with distributed fusion fuel is the crystalline solid Li_2DT, or lithium hydride (LiH) with hydrogen isotopes deuterium (D) and tritium (T) in equal proportions instead of H. The crystal structure is cubic NaCl type. Some properties are:

(a) The mass density of Li_2DT is ≈ 0.88 g cm^{-3}, and the number density of Li atoms of atomic mass 7 is 6×10^{22} cm^{-3}.

(b) The crystalline solid melts at about 700 °C, and latent heat of melting is ≈ 40 kJ $mole^{-1}$. Thus, a sphere of radius 1 m, containg 4×10^5 moles, requires energy 16 GJ for complete melting. The molten solid is corrosive to metals, restricting materials used for containment.

(c) Because the masses of Li, T and D are comparable (7, 3 and 2 atomic mass units respectively), thermalization time is short.

(d) The ionization of Li to Li^{3+} requires energy 5.4 + 75.8 + 122.6 = 203.8 ev, and ionization of D or T requires 13.6 ev, a total of 217.4 ev.

(e) A sphere of LiD with radius 2 m is capable of fully absorbing all products of fusions near the center. X-ray bremsstrahlung from the focal volume also will be largely absorbed, mean free path for 10 kev X-ray photons being

0.5 m. There is then little waste of input energy used in creating the conditions for fusion.

(f) LiD is a recognized breeder for T due to reactions

$$^{7}Li + {}^{1}n \rightarrow {}^{4}He + {}^{3}T + {}^{1}n - 2.47 \text{ Mev}$$

$$^{6}Li + {}^{1}n \rightarrow {}^{4}He + {}^{3}T + 4.8 \text{ Mev}$$

by the stable isotopes ^{7}Li and ^{6}Li present with abundances 92.5 % and 7.5 % respectively.

Option (ii) is to concentrate fusion fuel, possibly in encapsulated form, into a cavity in the converging medium toward which the shock waves converge. For example, DT fuel in a frozen state may be coated onto the inside of the wall of a spherical capsule of appropriate material (e.g. glass, plastic, metal), and the capsule then embedded in the converging medium in the appropriate position (centered on the focus).

3. Diagrams

Fig. 1 shows schematically the simplest variant of the shock wave fusion reactor. With reference to Fig. 1 converging medium 1, which has the density of a solid or liquid, is separated by wall 2 from chamber 3 for combustion of fluid chemical explosive ("combustion chamber") with substantial outermost wall 4. Pins 5 ensure that converging detonation wave 6 is spherical in shape, so that it launches spherical converging shock wave 7 in medium 1. Fluid explosive enters at port 8 and exits at port 9. Facility for heat extraction is not shown.

Fig. 1b and Fig. 1c illustrate schematically the method for generating detonation waves of large wavefront area and desired shape in fluid explosive. With reference to Fig. 1b, incipient corona-type discharges from the tips of the pins 1 ignite the fluid explosive at the tips of

the pins, thereby creating converging spherical detonation wave 2 which eventually launches a converging spherical shock wave in medium 3.

With reference to Fig. 1c microdischarges over the surface of dielectric plate 1 coverged by wire mesh ignite chemical explosive simultaneously over a spherical surface, thereby generating converging detonation wave 2 which later launches a converging shock wave in medium 3.

Fig. 1 d shows a standard circuit for generation of the high voltage pulse which is applied between the electrodes in Figs 1b and 1c. Capacitor C is charged through charging resistor R_c to high negative voltage - V with respect to earth, and triggering of spark gap S (or equivalently thyrotron S) by trigger pulse at T then discharges C through load resistor R_L, providing output high voltage pulse + V. The voltages required are envisaged to be in the 10 - 50 kV range, and simultaneity or timing is controllable to within accuracy of order 1 μs or less.

Fig. 2a and Fig. 2b shows schematically two methods for launch of spherical shock waves by mechanical impact.

With reference to Fig. 2a spherically shaped "hammer heads" 2 strike the spherical surface of converging medium 1, or the wall of converging medium 1, at all points simultaneously. The "hamnmer heads" are interconnected by interleaving plates so that the whole forms the inner of two concentric spherical walls of a "combustion chamber" for chemical explosive". A converging detonation wave 4 initiated at pin tips 3 accelerates the hammer assemby as a whole so that the "combustion chamber" expands until its inner wall 2 strikes the wall of medium 1.

Fig 2b shows simultaneous mechanical impacts over the surface of the converging medium 1 due to projectiles 2 which have been accelerated to high velocities by

explosive charges or chemical fuel burning in regions 3 triggered by individual independent sparks in plugs not shown. Timing of mechanical impacts may be controlled by timing spark ignitions in response to feed-back signals.

Facility to launch two or more shockfronts in rapid succession is desirable for arranging collisions between shockfronts in certain circumstances. Two methods for doing this are depicted in Fig. 2c and Fig. 2d. With reference to Fig. 2c, "delay medium" L has interfaces with the converging medium on the inside and some external medium on the outside with suitable transmission and reflection coefficients. Repeated reflections within L deliver waves 1, 2, 3 of progressively diminishing amplitude when wave W enters from the outside, and similarly deliver waves 1', 2' and 3' of progressively diminishing amplitudes when wave W' enters from the inside. Successive shock waves are separated in time by the time to propagate twice the thickness of the delay plate.

Fig. 2d depicts a spiring-loaded projectile which delivers a double-impact to a target. With reference to Fig. 2d the first impact occurs when part 1 of the projectile hits the target, and the second impact ocurs when part 2 of the projectile hits part 1, closing gap 4 by compression of the spring 3.

Fig. 3 shows three types of volume in a uniform medium reactor (UMR) where particle energies can exceed the threshold energy for useful fusion power production.

Fig. 3a shows a spherical focal volume.

Fig. 3b shows a shell volume where concentric spherical shockfronts collide, one converging and one diverging.

Fig 3c shows a tubular-ring volume where non-concentric spherical shockfronts, both converging, collide. The spherical shockfronts 1 and 2 converge respectively toward the foci F_1 and F_2 without ever reaching these

foci. The heavy arrows indicate "jetting" of particles toward the center of the ring whose radius shrinks to zero.

Fig. 4 shows three shapes of focal cavity toward which spherical shock waves converge in a solid or liquid medium, a non-melted cavity wall being required if the converging medium is liquid. In each case material of the converging medium is "off-loaded" into the cavity when the converging shockfront is reflected at the cavity wall.

In Fig. 4a off-loaded material forms a dense spherical shell which implodes toward the center of the focal cavity, which is the focus of the original converging shock wave. Fusion fuel within the cavity, which may be a frozen layer on the inside of a cavity wall material, is compressed to high density by the implosion, so that fusion threshold is exceeded.

In Fig. 4b a bi-conical focal cavity is depicted, which has the shape of a pair of right circular cones positioned back-to-back on the same circular base. The converging spherical shockfront encounters first the tips of the bi-cone, where injection of medium material releases pressure in the converging shockfront. As the shockfront continues to converge injection occurs closer and closer to the base of the bi-cone. The result is that particles injected into the focal cavity approach the center of the cavity in the form of oppositely directed jets.

In Fig. 4c a multiple bi-conical cavity is depicted. In its simplest form it comprises three bi-concical cavities protruding from a common spherical surface in three mutually orthogonal directions, so that three pairs of opposite jets (in total six jets) in mutually orthogonal directions collide at the center of the cavity.

Fig. 5 depicts a method for replacement of focal cavities. Prefabricated focal cavities 1 and 2 are embedded in a cylindrical column of converging medium material 3 which is fed through the sphere of converging medium 4 with outer boundary 6 so that each cavity can come into the focal position for spherical converging shock wave 5. A cylindrical column of solid converging medium is pushed through liquid converging medium so that each prefabricated focal cavity is positioned correctly for each fusion burst. If the sphere of converging medium is solid the column of converging medium would require to pass through a tight-fitting hole with suitable lubricant for shock wave impedance matching in order to avoid strong reflection at the sphere-column interface.

Fig. 6 depicts a pair of paraboloids of revolution which are coaxial and are positioned back-to-back. Between the paraboloids is a planar slab 3 of gaseous chemical explosive which is liquid or chemical for rapid renewal between fusion bursts. Plane shock waves are launched in opposite axial directions by the chemical explosive in response to appropriate detonation, Figs. 1b and 1c depicting possible detonation methods. After reflections at the paraboloid boundary surfaces the plane shock waves converge to foci 1 and 2. A cavity is shown to surround focus 2, and a similar cavity could also surround focus 1. The symmetrical conditions enable the relative performances with and without focal cavities to be compared. An important advantage of the bi-paraboloid system shown in Fig. 6 is the relative ease with which focal cavities can be renewed, because the generation of the shock waves is separated from the mechanism for cavity replacement. The same sort of advantages occur for heat fransfer from the converging medium.

Fig. 7 depicts a converging medium 4 with ellipsoidal boundary surface over which chemical explosive is distributed in a thin layer 3. Fluid chemical explosive is supplied also to a small cavity 2 surrounding one focus. A point chemical explosion in cavity 2 generates a spherical shock wave which diverges from the focus 2 until reflected at the ellipsoidal surface of medium 4. The reflection converts the spherical wave diverging from focus 2 into a spherical wave converging toward focus 1. Chemical explosive spread uniformly over the ellipsoidal surface of medium 4 (possibly fluid explosive contained by a thin surrounding chamber 3) is triggered by the reflection. A sheet of piezoelectric transducer may aid the triggering by providing accurately timed sparks at each surface element. Provided that local triggering is timed accurately in response to reflection at different surface elements, the sheet explosive will generate a shockfront of the same type as the reflected shock front, which thereby is amplified. When the reflected amplified shockfront reaches focus 1, it may be strong enough to create conditions for a useful rate of fusion reactions. Strong casing 7 contains the explosions. In order for repetition the chemical fluid supplied to focal cavity 2 and supplied also to the surface chamber 3 should be fluid. A feed tube with input at 5 and output at 6 is shown for the former supply, but that for the latter supply is not shown.

4. Some Engineering Design Considerations

(i)Renewal of Focal Cavities

An unwelcome complication for the CFR variant of reactor is the need to renew the focal cavity after each fusion burst, or at best one per several fusion bursts. Continual replacement is posible by arranging to position

new prefabricated focal cavities at the focal position after each burst.

In the case of spherical geometry for the converging medium, it may be possible to introduce focal cavities with thin walls of a material with high melting point into converging medium which is liquid at operating temperature. Indeed, in the case when the converging medium is Li_2DT, in liquid form, it may be possible to feed through the liquid a column of solid Li_2DT containing prefabricated focal cavities, these cavities coming into the focal position before the column melts. If the converging medium is solid Li_2DT then the column must be pushed through a tight-fitting hole in the converging medium with suitable liquid lubricant to prevent reflections at the column-medium interface.

The ideal geometry for cavity replacement is cylindrical, but convergence factor is the difficulty. If a convergence factor of 100 is required for spherical geometry, then factor 10,000 is required for cylindrical geometry.

A compromise may be the bi-paraboloid geometry depicted in Fig. 6. Here the mechanism for renewal of focal cavities is separated from apparatus for generating shock waves.

(ii) Heat Transfer

Both variants of reactor are efficient in that the energy of particles liberated in fusion reactions is absorbed by the converging medium. Moreover, unused shock wave energy also is absorbed in the converging medium, which amounts to recyling much of the input energy.

Transfer of heat from the converging medium to an external body is required in order to obtain useful power output. In the case of a liquid converging medium the simplest method for heat transfer may be a through-flow of liquid medium. Indeed outflow of medium in liquid form

might be balanced by inflow of medium in solid form, a particularly efficient extraction mechanism because of latent heat of melting.

In the case of the UMR variant of reactor with spherical geometry, continuous throughput of converging medium material may be impractical. There is always the option of alternating intervals of power generation with intervals of cooling during which the shock generation need not ocur. A sphere of Li_2DT of radius 1 m requires some 16 GJ in order to change from solid to liquid state, and therefore has the capacity to store a substantial amount of heat. Moreover, the store of fusion fuel is enormous for a sphere of Li_2DT with radius 1 m. Indeed Li_2DT is a breeder of tritium (see discussion of feature 5).

(iii) Choice of Reactor Type

In regard to the choice between the UMR and CFR variants of reactor, only the consideration of threshold attainment may favour the CFR variant. The much greater simplicity of the UMR variant due to absence of cavities strongly favours this type, provided that achieving threshold condition presents no severe problems.

The type of reactor contemplated is a small efficient and mobile installation, in contrast to conventional power stations which are large immobile installations.

5. Principle of Operation and Estimate for Pefomance

Let an impact at the surface of a solid medium displace atoms in a thickness λ of the medium, atoms deeper in the medium being unaffected. The displaced atoms pile up at the leading edge of a layer of thickness λ, producing rarefaction in the remainder of the layer. This structure, a compressed layer followed by a rarefied layer, propagates through the medium as a shock wave. The

density and pressure profile of a plane shock wave does not change during propagation, neglecting dissipation (i.e. loss of energy by heating or exciting the propagation medium). The number of particles which carry the wave at any instant continues to be the number of particles of undisturbed medium in volume $S\lambda$, where S is the constant shock wavefront. However, the number changes during propagation of a converging shock wave due to decrease of S. Then conservation of energy requires that the energy per particle increases, being proportional to S^{-2} if λ remains constant. The energy per particle is partly kinetic energy of forward motion and partly potential energy of medium compression, both contributions increasing with convergence.

Adopting the rest frame of the shock wave, the medium enters the wave with velocity $- v_1$, is compressed in the wave, and leaves the wave with velocity $- v_2$, rather as air enters a jet engine, is compressed, and is blown out again. The analogy with the jet engine is more exact for a detonation wave because energy is being continually fed into a detonation wave by combustion of the explosive gas, whereas in a passive shock wave there is no such fuel burning. Expulsion of fluid with mass density ρ_2 and velocity v_2 through area S_2 in a time δt represents loss of momentum $(\rho_2 S_2 v_2 \delta t)v_2$, which implies "jet-engine" force $\rho_2 v_2^2 S_2$ on the compression layer. Incoming material loses momentum $(\rho_1 S_1 v_1 \delta t)v_1$ in time δt, which implies stopping force $\rho_1 v_1^2 S_1$. The stopping force on the leading edge of the compression layer and the jet reaction force on the trailing edge have a pincer action on the compression layer, maintaining the compression.

For a plane shock wave equilibrium between the stopping force applied to inflowing fluid and the jet force applied to expelled fluid causes a stable situation in the absence of dissipation. For a converging shock wave this stability is lost. The thickness λ of the layer of

undisturbed medium which conveys the shock wave clearly is constant in the case of the plane shock wave, and it may also remain constant in the case of the converging shock wave (at least for large radii r). However, the shape of the pressure wave now changes as the wave propagates; specifically, the pressure rise steepens and the peak pressure increases as r decreases for the converging shock wave (unlike the plane wave). If Δr_c is the thickness of the leading compressed layer and Δr_r is the thickness of the following rarefied layer, then in order to maintain constant the total thickness λ the latter must increase as the former decreases. We assume

$$\lambda = \Delta r_c(r) + \Delta r_r(r) = \text{constant} \qquad (1)$$

where $r \gg \lambda$. A consequence of (A1) is that the number $N(r)$ of particles carrying the wave at radius decreases in proportion to r^{-2} because surface area $S(r)$ decreases as r^2 for a spherical wave. Thus

$$N(r) = n_o(4\pi r^2 \lambda) \propto r^2 \qquad (2)$$

If we assume, further, that the energy W_s of the shock wave is approximatly conserved during convergence from initial radius r_o to final radius r_f, then the energy per particle $w(r)$ must increase in proportion to r^{-2}. That is,

$$w(r) = \bar{m}u^2/2 + V(r) = W_s/N(r) \propto r^{-2} \qquad (3)$$

where $u(r)$ is the velocity of the average particle with mass $\bar{m}$ and $V(r)$ is the potential energy of the average particle due to compression of the medium. How the total energy is distributed between kinetic and potential forms is of little consequence, provided that the potential energy $V(r)$ is not transfered into a reflected wave. Indeed there may be periodic conversion of particle energy from kinetic to potential form and back to kinetic form. The pressure $p(r)$ of the shock wavefront at times of maximum potential energy may be expressed by

$$p(r) = n(r)w(r) \qquad (4)$$

where n(r) is the density of particles in the compressed layer.

In order to obtain a reasonable rate of fusion reactions, we require to transfer to some particles energy as large as about 10 kev. If this energy is entirely in kinetic form, then a deuteron with mass twice the hydrogen mass has velocity $v_D \approx 10^8$ cm s^{-1}. In principle, energy stored as potential energy due to elastic compression of the medium can always be converted into kinetic form, so the velocity v_D has a definite physical meaning. The deuteron partial pressure required for fusion is therefore given by

$$p_D(r) = n_D(r)w_D(r) = 4.8 \times 10^{14}C \quad \text{dyne cm}^{-2} \qquad (5)$$

where we substitute

$$w_D = 10 \text{ kev}, \qquad n_D(r) = 3 \times 10^{22} C \quad \text{cm}^{-3} \qquad (6)$$

in which C is a compression factor (the ratio of particle density in the compressed layer to particle density in the undisturbed fluid). Pressures of order several megabar (several times 10^{12} dyne cm^{-2}) have been measured in solids for non-focussed shock waves. The hope is that focussing will increase this pressure by a factor of about 100.

To summarise, subject to plausible assumptions, energy per particle in a converging spherical shock wave increases during convergence as the inverse square of the radius of the shock wave, so that after convergence from initial radius r_o (at launch) to final radius r_f (the radius of the "focal volume"), the energy per particle w(r) will have increased by factor $(r_o/r_f)^2$. Finally, we have the value $w(r_f)$ = 10 kev. For a "convergence factor" r_o/r_f = 300, the initial particle energy must then have the value $w(r_o)$ = 0.1 ev. The smallest focal volume achievable for convergence factor 300 probably has a radius of a few millimeters (since we may expect $r_f \approx \lambda$). Adopting r = 3 mm, it then follows that r_o = 90 cm.

The initial energy W_s of the shock wave is given by

$$W_s = 4\pi r_o^2 \lambda n_o w(r_o) = 10 \text{ MJ} \tag{7}$$

where we use the values

$$r_o = 90 \text{ cm}, \quad \lambda = 1 \text{ mm},$$
$$n_o = 6 \times 10^{22} \text{ cm}^{-3}, \quad w(r_o) = 0.1 \text{ ev} \tag{8}$$

The value for n_o is that for LiH (or Li_2DT). The value for $w(r_o)$ gives an atom of Li velocity 1.65 km s^{-1} and a deuteron velocity 3.1 km s^{-1}, which are reasonable for shock waves launched by chemical explosives.

There arises the question of how many particles can acquire energies of order 10 kev in the above manner. One obvious limit is the energy available in the shock wave, W_s = 10 MJ. The maximum number of particles that can be given energy 6 kev is

$$N(6 \text{ kev}) = W_s/w(r_o) = 10^{22} \tag{9}$$

The volume of undisturbed medium occupied by 10^{22} particles is

$$V_N = \rho_o/\bar{m} \simeq 0.1 \text{ cm}^3 \tag{10}$$

where for Li_2DT we have the values ρ_o = 0.88 grm cm^{-3} and $\bar{m} = 4.75m_H$, where m_H is the mass of a hydrogen atom. The radius of a sphere with volume (10) is r_N = 3 mm.

We conclude that a sphere of Li_2DT of radius 90 cm can provide fusion conditions within a volume of radius 3 mm which contains some 10^{22} particles, assuming that there is no loss of shock wave energy between launch and a focal volume of radius 3 mm. If there is such loss, so that a fraction f of shock wave energy reaches the focus, then the initial energy of the shock wave must be increased from W_s to W_s/f, which may well require that its radius is increased by the factor $f^{-\frac{1}{2}}$. If f is 10 %, then $f^{-\frac{1}{2}}$ = 3.16, and the required sphere must have radius ≈ 3 m.

There remains the question of how much fusion energy will be released per burst. If deuterons and tritons in the focal volume have kinetic energies w_D^* and w_T^* respectively, then the relative kinetic energy of a deuteron (that in the rest frame of a triton) is

$$w_{DT} = w_D^* + w_T^* = 6 + 4 = 10 \text{ kev} \qquad (11)$$

where we assign the value $w_D^* = 6$ kev, and hence $w_T^* = 4$ kev. The temperature θ appropriate for a Maxwellian distribution of relative velocities, is

$$\theta = 2w_{DT}/3 = 6.67 \text{ kev} \qquad (12)$$

The fusion rate for a single deutron of energy w_{DT} interacting with tritons at rest with density n_T is

$$\Gamma = \langle v_{DT}\sigma_{DT}\rangle n_T = 10^6 C \quad s^{-1} \qquad (13)$$

where we use $\langle v_{DT}\sigma_{DT}\rangle = 3.6 \times 10^{-17} cm^3 s^{-1}$ (from Fig. B2, appendix B) and $n_D = 3 \times 10^{22}$ C cm^{-3} (appropriate for Li_2DT), C being a compression factor. The total number of fusions is obtained by multiplying by the total number of deuterons in the focal volume, namely N/3 where N is given by (9). Energy relasaed per DT fusion is $\epsilon_{DT} = 17.7$ Mev $= 2.82 \times 10^{-12}$J, so fusion power is

$$P_F = 10^{16} C \quad \text{watt} \qquad (14)$$

If the fusion rate persists for time $\tau = C^{-1}$ ns, the energy released is 10 MJ, which equals the input energy W_s , which is a gain factor of 2 since the input energy is not lost. The value for τ varies as C^{-1} if it is determined by cooling of the electrons by X-ray bremsstrahlung.

APPENDIX A: CONVERGING SHOCK WAVES

(i) *The Newton sphere model for converging shock waves*

In the familiar exhibit known as Newton's spheres a line of touching identical steel spheres. S_1, S_2.... S_n, are suspended so that they can swing in the direction of the line. A half-swing of S_1 is brought to rest by the impact with S_2, launching a shock wave which propagates along the line and eventually causes S_n to complete the other half swing. Then S_n falls back and launches a return shock wave which has the same effect on S_1, and so on. The process continues many times because the shock propagates along the line of spheres with little dissipation.

Newton's spheres provide a vivid demonstration of conversion of kinetic energy of outside sphere S_1 into potential energy of elastic compression of the middle spheres S_2 .... S_{n-1}, and then back again into kinetic energy of end sphere S_n. The question is what happens when Newton's spheres have progressively decreasing mass. The decreasing mass situation models progress of a converging spherical shock wave provided that the masses of undisturbed layers of converging medium of constant thickness λ decrease in proportion to their surface areas. For each propagation step λ the number of particles $N(r)$ and the mass $M(r)$ decrease by the factor

$$\frac{N(r+\lambda)}{N(r)} = \frac{M(r+\lambda)}{M(r)} = \frac{(r+\lambda)}{r} \equiv \mu \qquad \text{(A1)}$$

Correspondence between layers of medium which convey a segment of a converging shock wave and a line of Newton spheres whose masses decrase in proportion to the masses of the layers of medium is depicted in Fig. A1.

We may treat λ as a mean free path for the particles which contribute to the mass M. Then we consider, in

effect, a sequence of Newton spheres of progressively decreasing mass which now are equally spaced from each other by distance λ. A disturbance propagates down the line of spheres, the energy being kinetic in form over the distance λ, and then for the short duration of inter-sphere impact becoming potential energy of elastic compression. We have to consider an elastic collision between adjacent spheres along the line. Initially the more massive sphere has velocity v_1 and the less massive sphere is at rest. After the collision the respective velocities, v'_1 and v_2, are found by conserving momentum and energy. Specifically

$$\begin{aligned} \mu M v_1 &= \mu M v'_1 + M v_2 \\ \tfrac{1}{2}\mu M v_1^2 &= \tfrac{1}{2}\mu M v'^2_1 + \tfrac{1}{2} M v_2^2 \end{aligned} \qquad \text{(A2)}$$

with solution

$$\begin{aligned} v_2/v_1 &= 2\mu/(1+\mu) \\ v'_1/v_1 &= (\mu-1)/(\mu+1) \end{aligned} \qquad \text{(A3)}$$

From (A1)

$$\mu = (1+\lambda/r)^2 \simeq 1 + 2\lambda/r \qquad \text{(A4)}$$

and from (A3)

$$v_2/v_1 - 1 = (\mu-1)/(\mu+1) \qquad \text{(A5)}$$

Assuming $\lambda \ll r$, so that $\mu \ll 1$, we have

$$v_2 = v_1 - (dv/dr)\lambda, \qquad \mu \simeq 1 + 2\lambda/r \qquad \text{(A6)}$$

where we assume $\lambda/r \ll 1$. Hence (A5) becomes

$$-(dv/dr)(\lambda/v) = \lambda/r \qquad \text{(A7)}$$

which integrates to

$$v(r)/v_o = r_o/r \qquad \text{(A8)}$$

where initial velocity is v for initial radius r.

The small remnant velocity v'_1 possessed by the more massive sphere represents energy transferred from the disturbance to the medium, which is energy lost by the shock wave. The amount lost per propagation distance λ is

$$\Delta W = W(v'_1/v_1)^2 \qquad \text{(A9)}$$

Since $\lambda/r \ll 1$,

$$\Delta W = -\lambda dW/dr, \qquad v'_1/v_1 \simeq \lambda/r \qquad \text{(A10)}$$

and we write (A9) as

$$dV/V = -\lambda dr/r^2 \qquad (A11)$$

which integrates to

$$V(r) = V_0 \exp(\lambda/r_0 - \lambda/r)$$
$$\simeq V_0 \exp(-\lambda/r) \qquad (A12)$$

Whilst $\lambda/r \ll 1$ it follows that $V(r) \simeq V_0$, which means little loss of shock wave energy. Exponential loss occurs for $r \simeq \lambda$.

The above analysis neglects inelastic collisions in which energy is transferred from the shock wave into excitation of the atoms of the medium. Excitation is associated with any change of state, for example change from solid to liquid, from liquid to gas, or from gas to plasma. Convergence from r_0 to a radius much less than r_0 implies r_0/λ elastic collisions and $r_0/\lambda*$ inelastic collisions. If $\lambda* > \lambda$ when particle energy becomes comparable to the energy of the excitation transition, neglect of inelastic processes may be justified.

(ii) Self-similar Hydrodynamical Solution

For a gas with specific heat ratio γ, the hydrodynamical shock equations expressing mass conservation, momentum conservation and entropy conservation take the form [1]

$$\delta(\ln \rho)/\delta t + u\delta(\ln \rho)/\delta r + \delta u/\delta r + (n-1)u/r = 0$$
$$\delta u/\delta t + u\delta u/\delta r + \rho^{-1}\delta p/\delta r = 0$$
$$[\delta/\delta t + u\delta/\delta r]\ln(p\rho^{-\gamma}) = 0 \qquad (A13)$$

where n = 1,2, or 3 for a plane, cylindrical or spherical wave respectively. The third equation expresses that the comoving derivative of entropy vanishes, specifically

$$dS/Dt = 0, \qquad S = c_v \ln pV + \text{const} \qquad (A14)$$

where c_v is specific heat at constant volume.

The equations (A13) applied to a spherical imploding shock wave of radius R(r) in a medium which has constant undisturbed density ρ_0 admit "self-similar" solutions which separates the time and spacial dependence of the

fluid parameters [2,3,1]. Instead of $u(r)$, $\rho(r)$ and $p(r)$ for the velocity, density and pressure of fluid behind the shockfront, we introduce respectively $v(\xi)$, $g(\xi)$ and $\pi(\xi)$, where $\xi = r/R(t)$ and

$$p(r,t) = \rho_o \dot{R}^2(t)\pi(\xi)$$
$$\rho(r,t) = \rho_o g(\xi)$$
$$u(r,t) = \dot{R}(t)v(\xi) \qquad \text{(A15)}$$

A dot is used to denote d /dt. The implication is that each of the spacial fields $u(r)$, $\rho(r)$ and $p(r)$ at time t can be obtained from those at time t_o by applying time-dependent scaling factors, different for each field.

Substitution of (A15) into (A13) yields

$$v' + (v - \xi)(\ln g)' + (n - 1)v/\xi = 0$$
$$(R\ddot{R}/\dot{R}^2)v + (v - \xi)v' + \pi'/g = 0$$
$$(R/\dot{R})d(\ln \rho_o^{1-\gamma}\dot{R}^2)/dt + (v - \xi)(\ln \pi g^{-\gamma})' = 0 \qquad \text{(A16)}$$

where dash means $d/d\xi$. Solution by separation of the variables t and ξ now is possible. One puts

$$R\ddot{R}/\dot{R} = \text{constant} = k \qquad \text{(A17)}$$

in which case it follows that

$$(R/\dot{R})d[\ln(\rho_o^{1-\gamma}\dot{R}^2)]/dt = 2k \qquad \text{(A18)}$$

so that (A16) reduce to

$$(v - \xi)(\ln g)' + v' + 2v/\xi = 0$$
$$kv + (v - \xi)v' + \pi'/g = 0$$
$$(v - \xi)[\ln(\pi g^{-\gamma})]' + 2k = 0 \qquad \text{(A19)}$$

which are linear ordinary differential equations for functions $v(\xi)$, $g(\xi)$ and $\pi(\xi)$. In solving (A19) conservation laws at the shockfront impose one set of boundary conditions, and conditions at launch impose further boundary conditions, assuming that the self-similar solution describes the motion at all times and is not merely an asymptotic approximation.

Integration of (A17) proceeds by writing $\ddot{R} = (d\dot{R}/dR)\dot{R}$. Then we obtain

$$d\dot{R}/\dot{R} = kdR/R \qquad \text{(A20)}$$

Integration leads to

$$\dot{R} = CR^k, \qquad R = A(t - t_o)^{\alpha}$$
$$\alpha = (1 - k)^{-1} \qquad \text{(A21)}$$

where C and t_o are integration constants, and $A = (C/\alpha)^{\alpha}$. When $k = 1$,

$$\dot{R} = mR, \qquad R = R_o \exp(mt) \qquad \text{(A22)}$$

where m and R_o are integration constants.

The choice for k amounts to imposing a boundary condition. We choose $k = -1$, in which case $\alpha = 1/2$ and the solution (A21) is

$$\dot{R} = C/R, \qquad R = A(t - t_o)^{\frac{1}{2}} \qquad \text{(A23)}$$

Then, by reference to (A15) we obtain

$$\dot{R} \propto R^{-1}, \qquad u(R) \propto R^{-2}, \qquad p(R) \propto R^{-2} \qquad \text{(A24)}$$

which is in agreement with (A8).

(iii) References

[1] Ya. B. Zel'dovich and Yu. P. Raizer, *Physics of shock waves and high-temperature hydrodynamical phenomena* , eds. W.D. Hayes and R.F. Probstein, vol II, Academic Press, New York, 1967, pp. 794-806.

[2] G. Guderley, Luftfahrt-forsch. 19 (1942), 302.

[3] K.P. Stanyukovich, *Unsteady motion of continuous media*, Engl. trans., ed. M. Holt, Academic Press, New York (1960).

APPENDIX B: ENERGY OF SHOCK-INDUCED FUSION BURSTS

(i) Fusion Reactions and Cross Sections

In order to understand how the new invention differs from conventional ideas on fusion reactors it is necessary to outline the theoretical basis for nuclear fusion. We consider only the conventional D-D and D-T reactions, although others are possible. These reactions and the energies of the reaction products are

$$^{2}D + {}^{2}D \rightarrow \begin{cases} {}^{3}He(0.82\ Mev) + {}^{1}n(2.45\ Mev) \\ {}^{3}T(1.01\ Mev) + {}^{1}H(3.02\ Mev) \end{cases} \qquad (B1)$$

and

$$^{2}D + {}^{3}T \rightarrow {}^{4}He(3.5\ Mev) + {}^{1}n(14.1\ Mev) \qquad (B2)$$

The two branches of the D-D reaction occur with about equal probability.

It is standard practice to express cross sections in terms of the kinetic energy of the bombarding particle (deuteron) as observed in the rest frame of the target particle (deuteron or triton). The cross section σ is a function of the kinetic energy of the bombarding particle in the rest frame of the target particle. If μ is the reduced mass given by $\mu^{-1} = m_D^{-1} + m_T^{-1}$, and v_{DT} is the relative velocity in the rest frame of the target particle, then the relative kinetic energy is

$$\begin{aligned} w_{DT} &= \tfrac{1}{2}\mu v_{DT}^2 = p^{*2}/2\mu \\ &= p^{*2}/2m_D + p^{*2}/2m_T = w_D^* + w_T^* \end{aligned} \qquad (B3)$$

where

$$\mu v_{DT} = m_D v_D = m_T v_T = p^* \qquad (B4)$$

(B3) expresses that the relative kinetic energy is the sum of the kinetic energies in the center of mass frame of reference with respect to which the particles have momenta $\pm$ p^*. In the case of a collision between a deuteron and a triton we have reduced mass

$$\mu = m_D m_T/(m_D + m_T) = 3m_D/5 = 2m_T/5 \qquad (B5)$$

Because a cross section is a function of the energy of the bombarding particle in the rest frame of the target particle, one brings all of the target particles (tritons) to rest in order to obtain the velocity distribution v_{DT} of the deuterons. Thermalization temperature θ (= kT) of this distribution is defined by

$$3\theta/2 = w_{DT} = w^*_D + w^*_T \quad \text{(B6)}$$

Cross sections are expressed as functions of relative kinetic energy $w_{DT} = \mu v^2_{DT}/2$, or an equivalent variable, $w'_D = m_D v^2_{DT}/2$, where m_D is the mass of the bombarding particle. From (B6) the different energy variables are related by

$$w_{DT} = w^*_D + w^*_T = (\mu/m_D)w'_D = 3\theta/2 \quad \text{(B7)}$$

For example, in the case of a deuteron with kinetic energy w^*_D = 6 kev in the center of mass frame of reference , we have $w^*_T = (m_D/m_T)w^*_D$ = 4 kev, and hence w_{DT} = 10 kev, so θ = 6.67 kev and w'_D = 16.67 kev. In summary

$$w^*_D = 6 \text{ kev}, \quad w^*_T = 4 \text{ kev}, \quad w_{DT} = 10 \text{ kev}$$
$$\theta = 6.67 \text{ kev}, \quad w'_D = 16.67 \text{ kev} \quad \text{(B8)}$$

These cross sections as functions of w'_D are given in Fig. B1, after ref. [1]. The analytical exprssions are

$$\sigma_{DD} = 182\, w'^{-1}_D \exp(-44.24/w'^{\frac{1}{2}}_D) \quad \text{barns}$$
$$\sigma_{DT} = 2.19 \times 10^4\, w'^{-1}_D \exp(-44.24/w'^{\frac{1}{2}}_D) \quad \text{barns} \quad \text{(B9)}$$

where w'_D is in kev and σ is in barns (1 barn = $10^{-24}cm^2$).

Because particles in the high energy tail of a Maxwellian distribution of velocities make the major contribution to fusion rate which is proportional to $v_{DT}\sigma(v_{DT})$, it is necessary to average this product over the distribution. The result, as a function of w'_D, is given in Fig. B2, after ref. [1]. The analytical expressions are

$$\langle\sigma_{DD} v_{DD}\rangle = 2.33 \times 10^{-14}\, \theta^{-\frac{2}{3}} \exp(-18.76/\theta^{\frac{1}{3}}) \quad cm^3s^{-1}$$
$$\langle\sigma_{DT} v_{DT}\rangle = 3.68 \times 10^{-12}\, \theta^{-\frac{2}{3}} \exp(-19.94/\theta^{\frac{1}{3}}) \quad cm^3s^{-1} \quad \text{(B10)}$$

RECTIFIED SHEET (RULE 91)
ISA/EP

The unequal sharing of energy among the particles which results from thermalization boosts fusion rate by factor

$$\gamma = \frac{\langle \sigma_{DT} v_{DT} \rangle}{\sigma_{DT} v_{DT}} = \frac{3.6 \times 10^{-17}}{2 \times 10^{-26} \times 1.26 \times 10^{8}} \approx 14.3 \quad \text{(B11)}$$

where values are given by (B8).

(ii) Bremsstrahlung Cooling Time

The question of the duration τ of power release raises the topic of cooling time. Cooling is caused primaily by X-ray bremsstrahlung (radiation due to acceleration of electrons by deflection in the Coulomb field of ions of charge Ze). The power P_b in watts radiated by N_e electrons in a plasma with charge-weighted ion density $\bar{n}_i$ and electron temperature θ_e is [1]

$$P_b = 2.14 \times 10^{-30} N_e \bar{n}_i \theta_e^{\frac{1}{2}} \text{ watt} \quad \text{(B12)}$$

where θ_e is in kev and $\bar{n}_i$ is in cm^{-3}, and where

$$\bar{n}_i = \sum_s n_{is} Z_s^2 \quad \text{(B13)}$$

with summation over different species s of ions, species s with charge $Z_s e$ being present in density n_{is}.

In the case of Li_2DT we have particle densities

$$n_{Li} = 6 \times 10^{22} C \ cm^{-3}, \quad n_D = n_T = n_{Li}/2 \quad \text{(B14)}$$

where C is the factor by which the medium is compessed relative to the undisturbed medium. In the case of full ionization we have

$$\bar{n}_i = (2 \times 9 + 1 + 1) n_D = 20 n_D$$
$$n_e = (2 \times 3 + 1 + 1) n_D = 8 n_D \quad \text{(B15)}$$

so that $\bar{n}_i n_e = 160\ n_D^2$. For a pure DT pellet we would have $\bar{n}_i n_e = 4 n_D^2$, so that presence of Li^{3+} increases radiative loss by a factor of 40.

Substituting into (B12) $\theta_e = 6.67$ kev and $\bar{n}_i N_e = \bar{n}_i n_e V = 160 n_D^2 V$, where $n_D = 3 \times 10^{22} C\ cm^{-3}$ and $V = 0.1\ cm^3$,

$$P_b = 8 \times 10^{16} C \text{ watt} \quad \text{(B16)}$$

This radiative power loss exceeds the fusion power (14) by a factor of about 8, and it must not prevent the threshold temperature for release of fusion power from

being attained. The question becomes what is the radiative loss energy during the time for ions to thermalize with electrons. Note that both fusion power P_F and X-ray bremsstrahlung power P_b are proportional to C, so that compression does not influence P_F/P_b.

If thermal energy in the focal volume is $W_{th} = 10$ MJ, as previously estimated, bremsstrahlung cooling time is

$$t_b = W_{th}/P_b \simeq 0.1\ C^{-1}\ \text{ns} \qquad \text{(B17)}$$

Radiative loss of energy is delayed by two considerations. The full ionization of atoms may not be achieved before the ions thermalize to ≈ 6 kev, and secondly the time for ions to share their energy with electrons is longer than the time for the ions to share energy among themselves (see below).

(iii) Energy Transfer Times

Two other time scales are of importance. One is thermalization time t_T, which is the time for particles with an arbitrary distribution of velocities to come to the Maxwellian distribution. The other is the time t_{eq} for hot positive ions to share their heat with cool electrons. The time t_T is important in order that the boost factor γ due to thermalization of deuteron energies can be realized quickly. The time t_{eq} is important because bremsstrahlung cools electrons, but not necessarily deuterons if the time for exchange of heat between deutrons and electrons exceeds cooling time for the electrons.

For t_T we use a formula derived by Spitzer [2] for particles of mass A_i (in atomic units) with charge Ze which are present in number density n_i:

$$t_T = \frac{11.4 A_i^{\frac{1}{2}} T^{\frac{3}{2}}}{Z^4 n_i \ln\Lambda} \simeq 40C^{-1}\ \text{ps} \qquad \text{(B18)}$$

Here factor $\ln\Lambda$ arises because multiple small angle deflections at long range statistically deviate a

particle through angle $\pi/2$ before a large deflection at small angle, and under the present conditions we may assume $\ln\Lambda = 6.7$. The values $A_i = 2$, $Z = 1$, $T = 10^8\ {}^oK$, and $n_i = 6 \times 10^{22}\ cm^{-3}$(for Li_2DT) yield $t_T = 40\ C^{-1}$ ns.

For cooling rate due to transfer of energy to relatively cold electrons, Spitzer [2] gives

$$d\theta_i/dt = -(\theta_i - \theta_e)/t_{eq} \qquad (B19)$$

where

$$t_{eq} = \frac{5.87\ A_e A_i}{n_i Z^2 \ln\Lambda}\left(\frac{T_e}{A_e} + \frac{T_i}{A_i}\right)^{3/2} \text{ sec} \qquad (B20)$$

For values, $A_i = 2$, $A_e = 1/1836$, $n_i = 6 \times 10^{22}C$, $Z = 1$ and $\ln\Lambda = 6.7$, we may reduce (B20) to

$$t_{eq} = 1.6 \times 10^{-26} C^{-1} (T_e/A_e + T_i/A_i)^{3/2} \qquad (B21)$$

Initially the term T_i/A_i is dominant, but after electron temperature exceeds about $T_i/1000$ the term T_e/A_e becomes dominant. Up to $T_e \approx 10^6\ {}^oK$ bremsstrahlung cooling rate is not a serious loss, so the question is how long does it require to heat electrons to $10^6\ {}^oK$. We put $T_e/A_e = 1836 \times 10^6\ {}^oK$, and obtain from (B20) $t_{eq} \approx C^{-1}$ps.

We conclude that cooling by bremsstrahlung is not delayed significantly by either thermalization among ions or by thermalization between ions and electrons.

(iv) Conventional Approaches to Nuclear Fusion

The ratio of fusion energy to thermal energy is

$$g = \frac{W_F}{W_{th}} = \frac{\langle\sigma_{DT} v_{DT}\rangle n_T N_D \epsilon_{DT} \tau}{(N_D + N_T) w_D} \qquad (B22)$$

Noting that $N_D/(N_D + N_T) = 1/2$ and $\epsilon_{DT}/w_D \approx 3000$ for $w_D = 6$ kev, and again taking $\langle\sigma_{DT} v_{DT}\rangle \approx 4 \times 10^{-17} cm^3 s^{-1}$ for $\theta = 6.67$ kev, it follows that

$$n_e\tau = 2 \times 10^{13} g \quad cm^{-3}s \qquad (B23)$$

where $n_e = n_D + n_T = 2n_D$. The relation (B23) is the Lawson criterion for DT fusion at $\theta \approx 10$ kev. It relates the time of confinement τ to the density n_e of the

confined plasma without consideration of practical limitations on n_e and τ in order to obtain a given gain factor, say $g = 1$.

In the two major approaches to fusion currently being researched the values of n_e and τ in (B23) are vastly different. For magnetic confinement, $n_e \approx 10^{13}$ cm^{-3} and $\tau \approx 1$ s. In the inertial confinement approach $n_e \approx 10^{25}$ cm^{-3} and $\tau \approx 1$ ps.

(a) The approach of longest standing employs magnetic fields to confine plasmas, but it continues to be difficult to confine a plasma at temperature $\approx$ 10 kev with density $\approx 10^{13}$ cm^{-3} for the required time $\tau \approx 1$ s. Confinement times in tokamaks are 10 - 100 times shorter than predicted, and modifications are being suggested [3]. A variety of magnetic confinement systems have been considered [4].

(b) Inertial confinement, a more recent approach, is usually implemented by irradiating isotropically a pellet of fusion fuel by focussed high-power laser pulses. An absorber layer surrounds a driver layer which encloses DT fuel. Rapid ablation of the absorber layer launches, as a reaction, an imploding shock wave which compresses the pellet to very high densities. Laser pulses of energy 1 - 1.5 kJ and duration 0.6 - 0.7 ns have compressed a pellet of fusion fuel from radius 150 μm to radius 30 μm (as revealed by X-ray bremsstrahlung images), the compressed densities being 20 - 40 g cm^{-3} implying $n_e \approx$ (0.5 - 1) x 10^{25} cm^{-3} (100 - 200 times the density of liquid DT) [5]. The aim is to achieve the high particle density before heat arrives. The neutrons produced indicate that the Lawson criterion (B23) with $g = 1$ still has not been met.

The possibility of replacing laser beams by heavy ion beams in the "inertial confinement" approach has been considered, but not yet tested [6]. The aim is to implode a spherical hollow shell comprising an outer heavy tamper

layer, a middle absorbing layer, and an inner frozen DT layer. The sudden heating of the absorber layer by the charged particle beam generates an implosion as a reaction to expulsion of the tamper, as happens with the laser beam radiaion. A beam current of a few mega-amperes delivers energy of a few mega-joules to the target in a time of perhaps 100 ns. Heavy ions are preferred to light ions as their kinetic energy is greater and their range in the target is smaller. In proposed devices, implosion velocity is calculated to reach 3×10^7 cm s^{-1}. Ignition is supposed to occur at "spark radius" 75 μm when pressure is 0.2 Tbar (= 2×10^{17} dyne cm^{-2}).

The present proposed shock wave fusion generator, in type A form, can implode a hollow shell of fusion fuel more effectively than the charged beam technique, because the driver is a hollow shell of much greater particle density with better isotropy.

(iv) References

[1] S. Glasstone and R.H. Lovberg, *Controlled thermonuclear reactions*, Van Nostrand, Princeton, N.J. (1960) pp. 6-32.

[2] L. Spitzer, *Physics of fully ionized gases*, Interscience Publ., New York (1956) pp 65-81.

[3] N. Rostoker et al., *Magnetic fusion with high energy self-colliding ion beams*, Phys. Rev. 70 (1993) pp. 1818-1821.

[4] F.F. Chen, *Alternate concepts in magnetic fusion* , Phys. Today, May (1979) pp. 36-43

[5] R.L. McCrory et al., *Laser compression and stability in inertial confinement fusion*, Plasma Phys. Contolled Nucl. Fus., 31 (1989) pp. 1517-1533.

[6] R.C. Arnold and J. Meyer-ter-Vehn, *Inertial confinement fusion driven by heavy-ion beams*, Rep. Prog. Phys. 50, (1987), pp. 559-606.

CLAIMS

1. Apparatus for generating nuclear power comprising

(i) a solid or liquid medium, herein referred to as a converging medium, in which a converging shock wave will propagate towards a focus,

(ii) shock wave generation means for launching a converging shock wave into said medium so that the shock wave converges towards the focus, and

(iii) fusion fuel either distributed within the converging medium or confined to a focal cavity in said medium,

the converging medium being such as to be capable of reducing the volume of a shock wave wholly by convergence of the shock wave towards a focus so that the energy per particle in the converged shock wave exceeds the threshold value for effecting fusion in said fuel.

2. Apparatus as claimed in claim 1 wherein the converging medium is such as to provide a convergence ratio, r_0/r_f, of at least 100.

3. Apparatus as claimed in claim 2 wherein the converging medium is such as to provide a convergence ratio, r_0/r_f, of at least 150.

4. Apparatus as claimed in claim 3 wherein the converging medium is such as to provide a convergence ratio, r_0/r_f, of at least 200.

5. Apparatus as claimed in any one of claims 1 to 4 wherein the shock wave generation means and the converging medium are so related that the final energy per particle of the particles conveying the converged shock wave exceeds the threshold

value for a useful rate of fusion reaction. said find energy preferably being at least 1 kev and more preferably at least 10 kev.

6. Apparatus as claimed in claim 5 wherein the shock wave generation means and the converging medium are so related so as to be capable of providing an energy per particle of at least. 15 kev.

7. Apparatus as claimed in claim 6 wherein the shock wave generation means and the converging medium are so related so as to be capable of providing an energy per particle of at least. 20 kev.

8. Apparatus as claimed in any one of claims 1 to 6 wherein the shock wave means is capable of generating repeated shock waves.

9. Apparatus as claimed in any one of claim 1 to 8 wherein the converging medium is spherical.

10. Apparatus as claimed in any one of claims 1 or 9 wherein the shock wave generating means is adapted to generate a spherical shock wave.

11. Apparatus as claimed in any one of claims 1 to 8 wherein the shock wave generating means is adapted to generate a cylindrical shock wave.

12. Apparatus as claimed in any one of claims 1 to 11 wherein the shock wave generating means is adapted to launch converging shock waves by providing impulsive pressure over a major fraction of the outermost surface of the converging medium or over a major fraction of an intermediate medium from which they are transferred to the converging medium.

13. Apparatus as claimed in claim 12 wherein detonation means are provided such that a detonation produced thereby provides the impulsive pressure to the surface of the converging medium.

14. Apparatus as claimed in claim 13 wherein the detonation means is adapted to provide a detonation wave in a chemical fuel or explosive.

15. Apparatus as claimed in claim 14 provided with a chamber surrounding the converging medium. said chamber serving to hold said chemical fuel or explosive.

16. Apparatus as claimed in claim 15 wherein the detonation means is adapted to provide a plurality of point electrical discharges or microsparks for initiating the detonation. uniformly distributed over a surface.

17. Apparatus as claimed in claim 16 wherein the detonating means has an array of pins uniformly disposed on the outer interior wall of the chamber so as to project into the chamber. said tips being the origin of said point electrical discharges or microsparks.

18. Apparatus as claimed in claim 17 wherein the pins are provided on an electrode and are of uniform spacing and uniform length. and the point electrical discharges or microsparks are initiated at the instant when a high voltage pulse is applied between the electrode with the array of pins and a further. suitably shaped electrode.

19. Apparatus as claimed in claim 16 provided with a layer of dielectric medium covered by a perforated (e.g. wire mesh) conductor in contact with the dielectric medium and the point electrical discharges or microsparks occur uniformly over those portions of the surface of the polarised dielectric material exposed through the perforated material. the polarisation being induced by a high voltage pulse applied

between the perforated conductor and a continuous conductor in contact with the other side of the dielectric medium.

20. Apparatus as claimed in claim 11 wherein the shock wave generating means provides impulsive pressure to the converging medium by mechanical impact.

21. Apparatus as claimed in claim 20 wherein projectiles, pistons or the like are provided for delivering impulsive pressure by for striking a large fraction of the area of the surface of the converging medium or the surface of an intermediate medium in contact with the converging medium.

22. Apparatus as claimed in claim 21 wherein impulse pressure is provided by said pistons or projectiles and the time of impact of the pistons is variable.

23. Apparatus as claimed in claim 22 wherein the variable time of impact is provided by virtue of shafts of the pistons being of adjustable length or by allowing a fluid converging medium to enter the piston cylinders to adjustable heights.

24. Apparatus as claimed in claim 20 wherein a converging detonation wave with the same shape as the shock wave to be launched is generated in a surrounding "combustion chamber" and used to accelerate an array of coupled "hammer heads" so that they impact the surface of the converging medium simultaneously.

25. Apparatus as claimed in claim 20 wherein projectiles are accelerated in an array of cylindrical "gun barrels" so that they impact a large fraction of the surface area of the converging medium (or of the wall containing the converging medium), the acceleration of each projectile being caused by ignition of chemical explosion in the head of the "gun barrel" by a spark timed in response to a feed-back signal generated by previous impacts for that "gun barrel".

26. Apparatus as claimed in claim 20 wherein projectiles comprising leading and following solid components coupled by a spring deliver double mechanical impulses to the surface of the converging medium. the first impulse occurring when the leading component strikes the surface of the converging medium and the second impulse occurring when the trailing component strikes the leading component.

27. Apparatus as claimed in any one of claims 11 to 26 provided with pressure sensors whereby the times of arrival (as measured by said sensors) at the surface of elements of wavefront reflected from the focus may be used to adjust the times of application of impulsive pressure to local regions of the surface of the converging medium or of an intermediate medium.

28. Apparatus as claimed in any one of claims 1 to 28 which is such that a spherical shock wave converging toward the focus can be made to collide at a position near to the focus with a spherical shock wave diverging from the same focus.

29. Apparatus as claimed in claim 28 in which the shock wave diverging from the focus is the reflection of a shock wave previously converging to the same focus. the reflection occurring either naturally or at the surface of a dense sphere (e.g. ballbearing) introduced into the converging medium in order to provide the reflection.

30. Apparatus as claimed in any one of claims 1 to 29 wherein the shock wave generating means is capable of launching two converging shock waves in rapid succession. wherein a shock wave W enters a delay medium within which a portion of its amplitude is trapped by multiple reflections at the outer and inner boundaries of the delay medium, the portions of the wave amplitude reflected at successive reflections at the inner boundary then leaving complementary transmitted portions of the wave amplitude which represent a train of waves of progressively diminishing amplitude following in the wake of W.

31. Apparatus as claimed in any one of claims 1 to 30 wherein the shock wave generating means is capable of launching shock waves converging toward different foci and said waves are made to collide either before they reach the foci or after they have been reflected by the foci.

32. Apparatus as claimed in claim 31 wherein the converging medium comprises two spherical caps of a common circular base with the property that the centre of one spherical cap lies in the other spherical cap whereby shock waves launched simultaneously at the surfaces of the spherical caps will collide in a ring on the mid-plane of the common circular bases. said ring shrinking to a point at the centre of the converging medium.

33. Apparatus as claimed in any one of claims 1 to 28 which is such that a shock wave is reflected repetitively from the focus and from the surface. alternatively converging toward the focus and diverging toward the surface.

34. Apparatus as claimed in claim 33 having two foci and the apparatus is such that a shock wave is reflected repetitively between either one of the two foci and the surface of the medium. and reflections from one focus (focus 1) alternate with reflections from the other focus (focus 2).

35. Apparatus as claimed in claim 34 wherein the two foci are the foci of an ellipsoid.

36. Apparatus as claimed in claim 34 wherein the two foci belong to two paraboloids which are aligned coaxially and pointing in opposite directions. hereafter termed "back-to-back" alignment.

37. Apparatus as claimed in any one of claims 1 to 36 wherein fusion fuel is distributed uniformly throughout the medium containing the two foci.

38. Apparatus as claimed in any one of claims 1 to 36 wherein fusion fuel is concentrated into a small cavity at one or other of the two foci.

39. Apparatus as claimed in claim 38 having provision for continuous or repetitive replacement of the fusion fuel.

40. Apparatus as claimed in claims 33 to 39 which is such that a sequence of chemical explosions in the cavity at focus 2 instigates a series of fusion bursts at the focus 1.

41. Apparatus as claimed in claim 40 wherein a shock wave returns from each fusion burst at focus 1 to trigger the next chemical explosion at focus 2. so that the sequence of fusion bursts becomes self-sustaining with period equal to the time for a shock wave to propagate from focus 2 to focus 1 and back again to focus 2. which is the "round-trip propagation" time.

42. Apparatus as claimed in claim 36 wherein chemical explosive in the planar layer which separates the two paraboloids launches plane shock waves in opposite directions into the paraboloid media. where they are converged to separate foci by reflections.

43. Apparatus as claimed in claim 42 wherein mechanical impact between the planar surfaces of the two paraboloids. or between the two surfaces of intermediate media. launches oppositely propagating planar shock waves into the paraboloids.

44. Apparatus as claimed in claim 1 wherein the converging medium is a continuous medium.

45. Apparatus as claimed in claim 44 wherein fusion conditions are attained in localized volumes of the medium selected from

(A) a small volume surrounding the focus toward which the shock waves converge, termed "focal volume":

(B) the volume of overlap of colliding shockfronts of the same shape and with opposite directions of propagation. so that at one instant of time the shockfronts are superimposed in their entirety;

(C) the volume of overlap of colliding shockfronts with general shape and general direction of propagation which intersect along a curve (providing a tubular volume of intersection) which moves as the shock fronts propagate. causing the phenomenon of "jetting".

46. Apparatus as claimed in claim 1 wherein the fusion fuel is provided in a focal cavity in the converging medium.

47. Apparatus as claimed in claim 45 wherein the converging medium incorporates a cavity in a liquid medium toward which shock waves converge so that the medium cavity boundary is encountered by the converging shock waves before the focus is reached.

48. Apparatus as claimed in claim 45 or 46 wherein the cavity is spherical and is concentric with a spherical converging shock wave adapted to be generated by the shock wave generating means.

49. Apparatus as claimed in claim 45 or 46 wherein the cavity has the shape of a pair of right circular cones positioned back-to-back on the same circular base (hereafter termed "bi-conical shape").

50. Apparatus as claimed in claim 45 or 46 wherein the cavity has the shape of a sphere from which protrude pairs of opposite directed right circular cones uniformly distributed in angle cover the surface of the sphere (hereafter termed "multiple bi-conical shape").

51. Apparatus as claimed in any one of claims 45 to 50 provided with means for replacing a focal cavity after one or more bursts of fusion energy wherein a column of solid converging medium material, or other suitable material, in which is embedded a line of prefabricated focal cavities is pushed forward into liquid converging medium so that a new cavity is brought into position for a subsequent converging shock wave.

52. Apparatus as claimed in claim 51 wherein the column of converging medium material, or other suitable material, is fed through a close-fitting hole in a solid sphere of converging medium with lubricant at the column-sphere interface suitable for minimising reflection loss for the converging shock wave at the said interface.

53. Apparatus as claimed in claims 51 or 52 wherein the prefabricated cavities are capsules with walls of suitable material (for example, plastic, glass or metal) into which the fusion fuel is concentrated.

54. Apparatus as claimed in any one of claims 45 to 53 wherein the fusion fuel is a layer of frozen DT on the inside surface of the capsule wall.

55. Apparatus as claimed in claim 51 or 53 wherein the converging medium is in the form of pair of coaxial paraboloids of revolution positioned back-to-back into which pairs of planar shock waves are launched at the mid-plans by renewable sheet explosive, each planar shock wave being brought to a focus by reflection at the boundary surface of each paraboloid. the advantage of this system being that

prefabricated cavities at the foci can be replaced with relative ease by replacing a portion of paraboloid containing the focal cavity.

56. Apparatus as claimed in any one of claims 1 to 55 wherein the converging medium absorbs unused shock wave energy.

57. Apparatus as claimed in any one of claims 1 to 55 wherein the converging medium absorbs the energy of the products of fusion reactions.

58. Apparatus as claimed in claim 57 which is such that heat extraction from the "converging medium" by outflow of converging medium material in liquid form balanced by inflow of converging medium material in solid form.

59. Apparatus as claimed in claim 58 which is such that heat is extracted from the "converging medium" by alternating intervals when the converging medium is being heated by repetitive bursts of fusion reactions with intervals when the converging medium is being cooled by heat transfer to a coolant circulated around the combustion chamber surrounding the converging medium. or other such surrounding chamber.

60. Apparatus as claimed in any one of claims 1 to 59 wherein the fusion fuel comprises deuterium and/or tritium.

61. Apparatus as claimed in any one of claims 1 to 60 wherein the converging medium comprises lithium hydride with deuterium (D) and/or tritium (T) in place of the most common isotope of hydrogen (H).

62. Apparatus as claimed in claim 33 wherein the converging medium is ellipsoid having a boundary surface over which chemical explosive is distributed in a thin layer and fluid chemical explosive is provided in a small cavity surrounding focus 2 whereby a point explosion in said cavity generates a spherical shock wave which

diverges from focus 2 until reflected at the ellipsoid surface. said reflection triggering the explosive at the boundary surface and converting the spherical wave diverging from focus 2 into a spherical wave converging towards focus 1.

63. Method of effecting fusion in fusion fuel either distributed within a converging medium or confined to a focal cavity in said medium. comprising providing a shock wave in the medium and reducing the volume of the shock wave by convergence of the shock wave towards a focus so that the energy per particle in the converged shock wave exceeds the threshold value for effeeting fusion in said fuel.

64. Method as claimed in claim 63 effected using an apparatus as claimed in any one of claims 1 to 61.

65. Apparatus for launching shock waves in any medium. or detonation waves in an explosive medium. wherein wavefronts of specified shape with large area and specified shape (e.g. spherical. cylindrical or other shape) are launched by detonation waves in chemical fluid explosive which have the same shape as the shock waves to be launched. the detonation waves having been ignited by an array of point discharges or microsparks which are uniformly distributed over a surface with the desired shape of wavefront.

66. Apparatus as claimed in claim 65 wherein the discharge or microsparks occur at the tips of pins having uniform spacing and equal length which protrude from the surface of a conducting medium whose shape is the desired shape of wavefront. the microsparks occurring at the instant when a high voltage pulse is applied between the electrode with the array of pins and other suitable shaped electrode.

67. Apparatus as claimed in claim 65 wherein the discharges or microsparks occur uniformly over those portions of the surface of a polarised dielectric slab which is not covered by a perforated (e.g. wire mesh) conductor in contact with the dielectric

surface. the polarisation being induced by a high voltage pulse applied between the perforated conductor and a continuous conductor in contact with the other side of the dielectric slab.

68. Apparatus as claimed in claim 67 wherein the discharges or microsparks occur between an array of pins of the type defined in claim 63 and a perforated conducting sheet (e.g. a wire mesh) held at a fixed short distance in front of the tips of the pins.

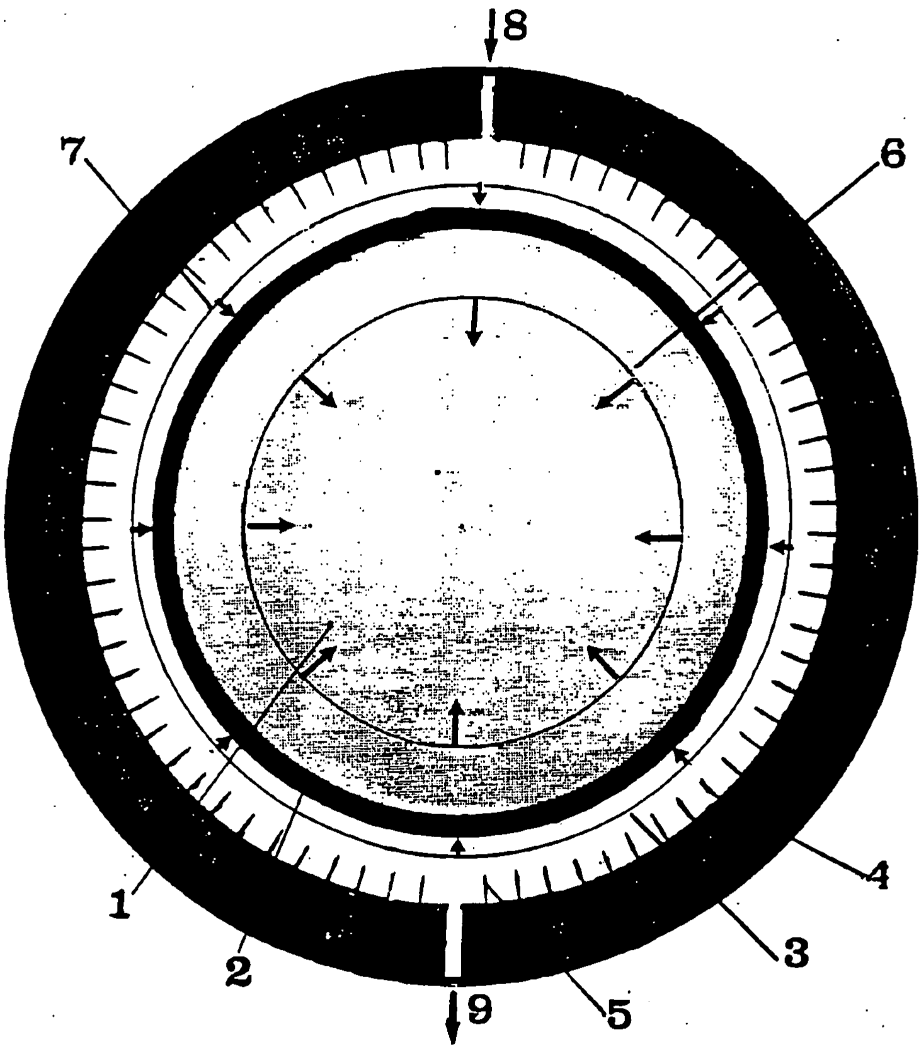


FIG.1a

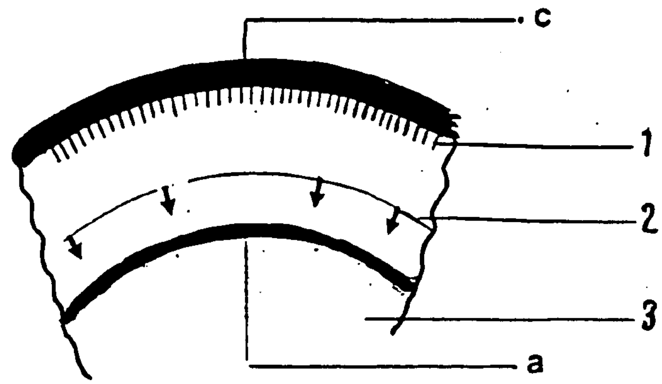


FIG.1b

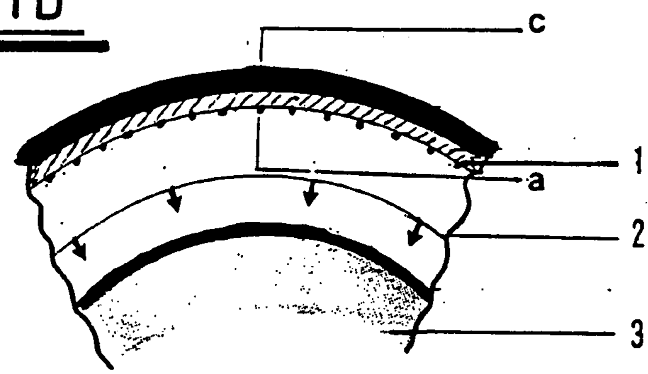


FIG.1c

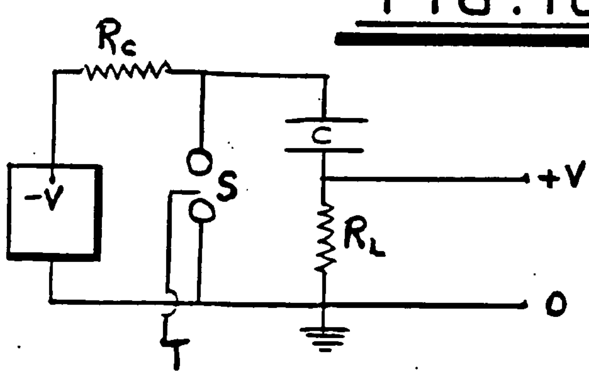


FIG.1d

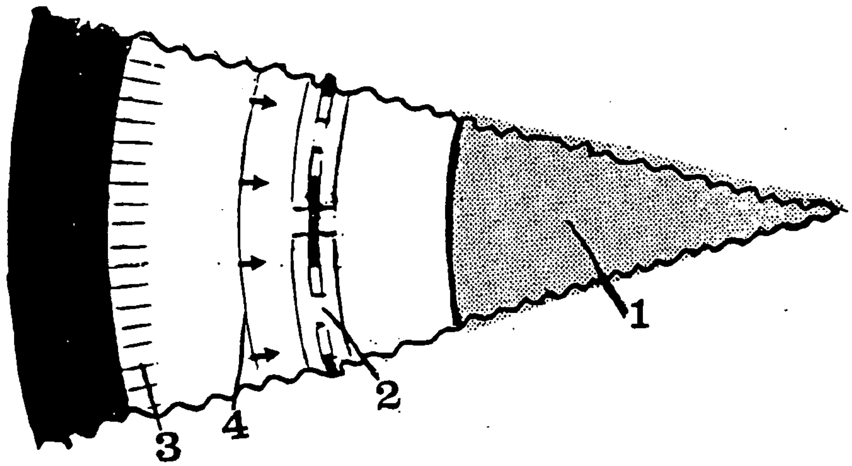


FIG. 2a

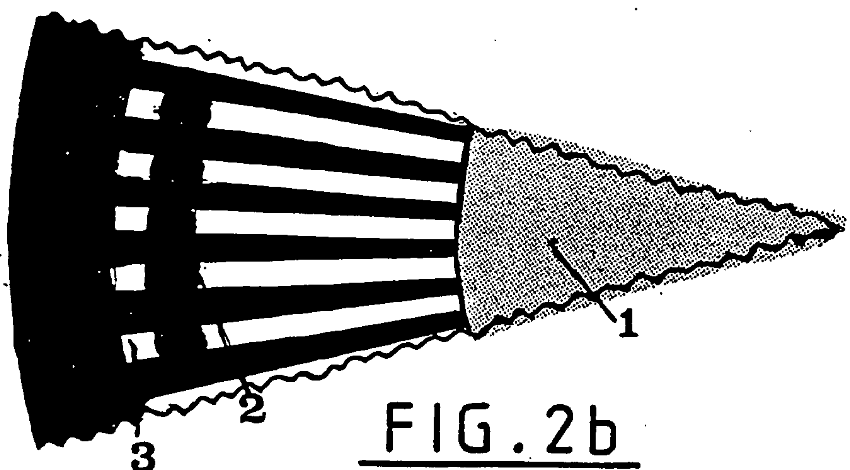


FIG. 2b

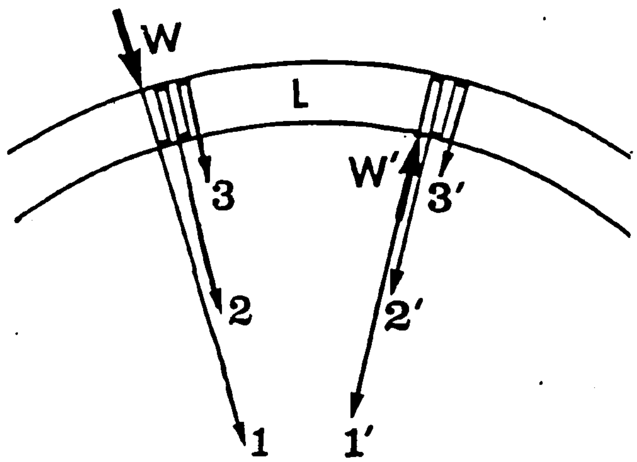


FIG. 2c

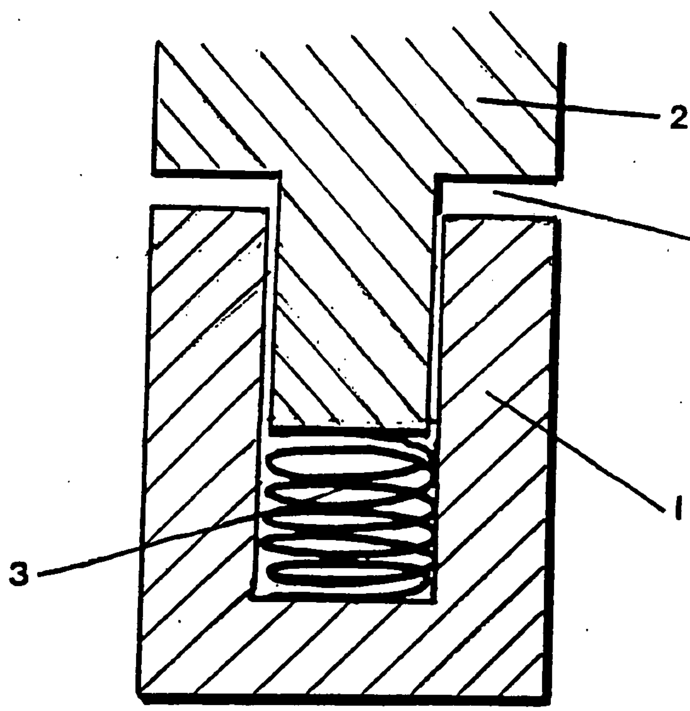


FIG. 2d

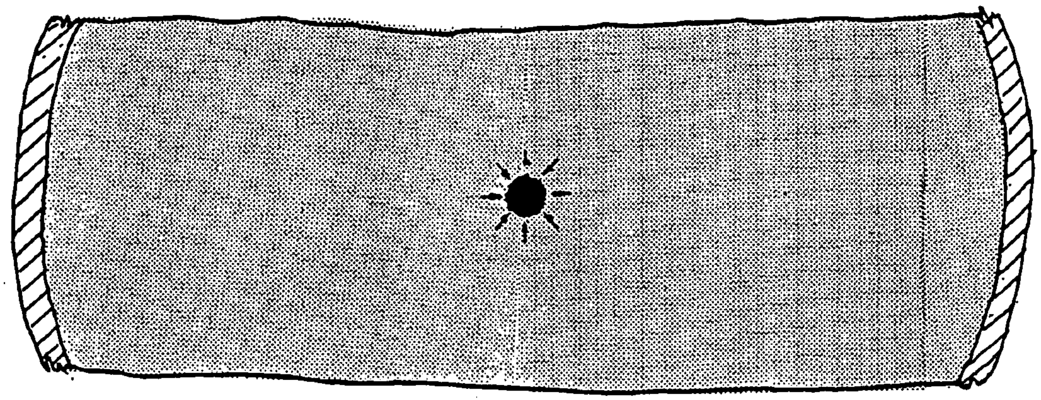


FIG.3a

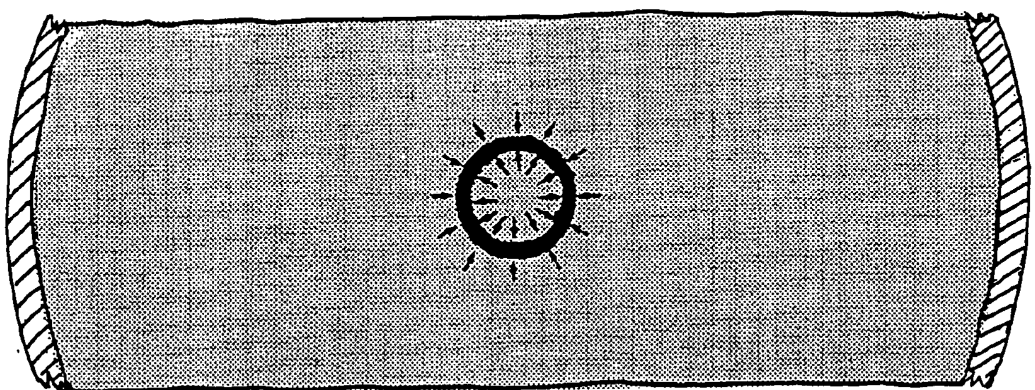


FIG.3b

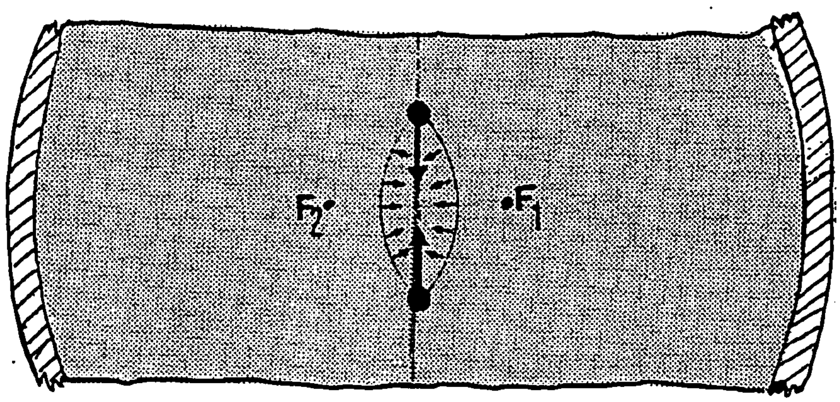


FIG.3c

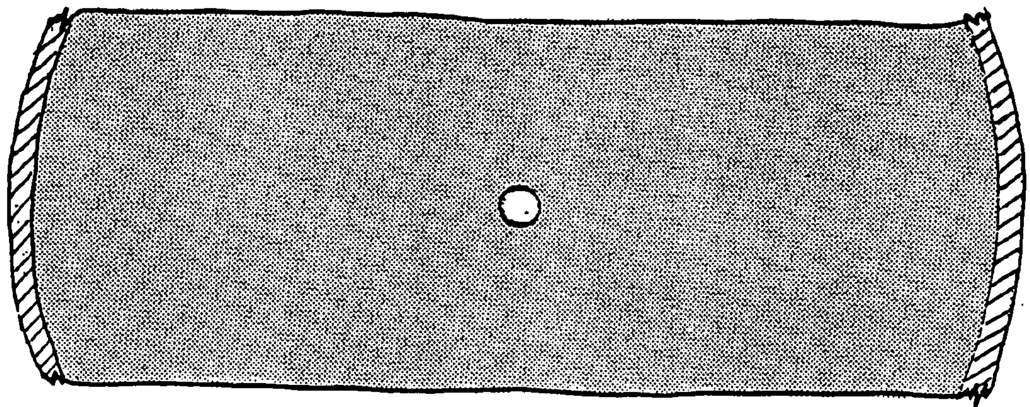


FIG.4a

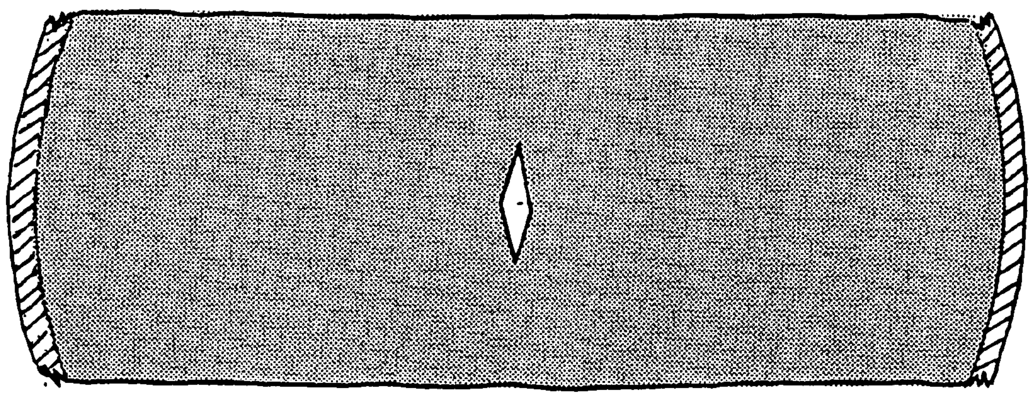


FIG.4b

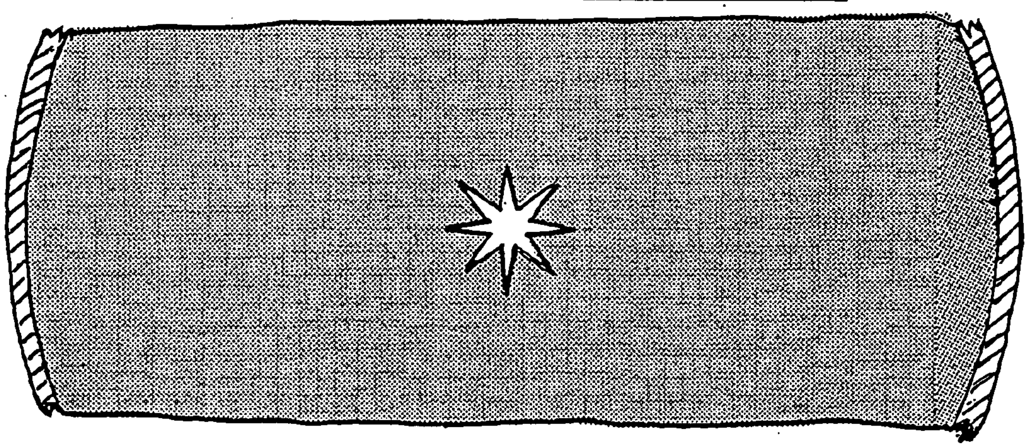


FIG.4c

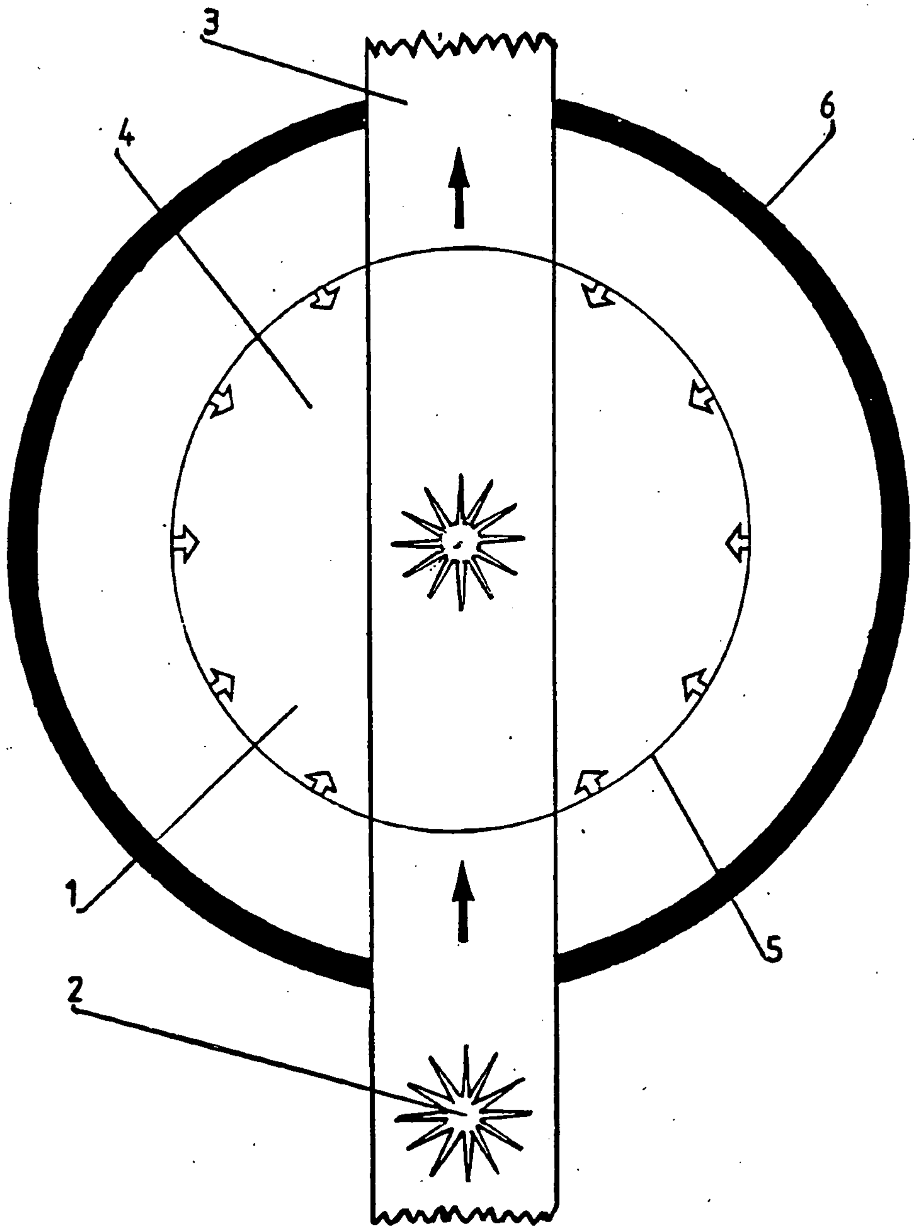


FIG.5

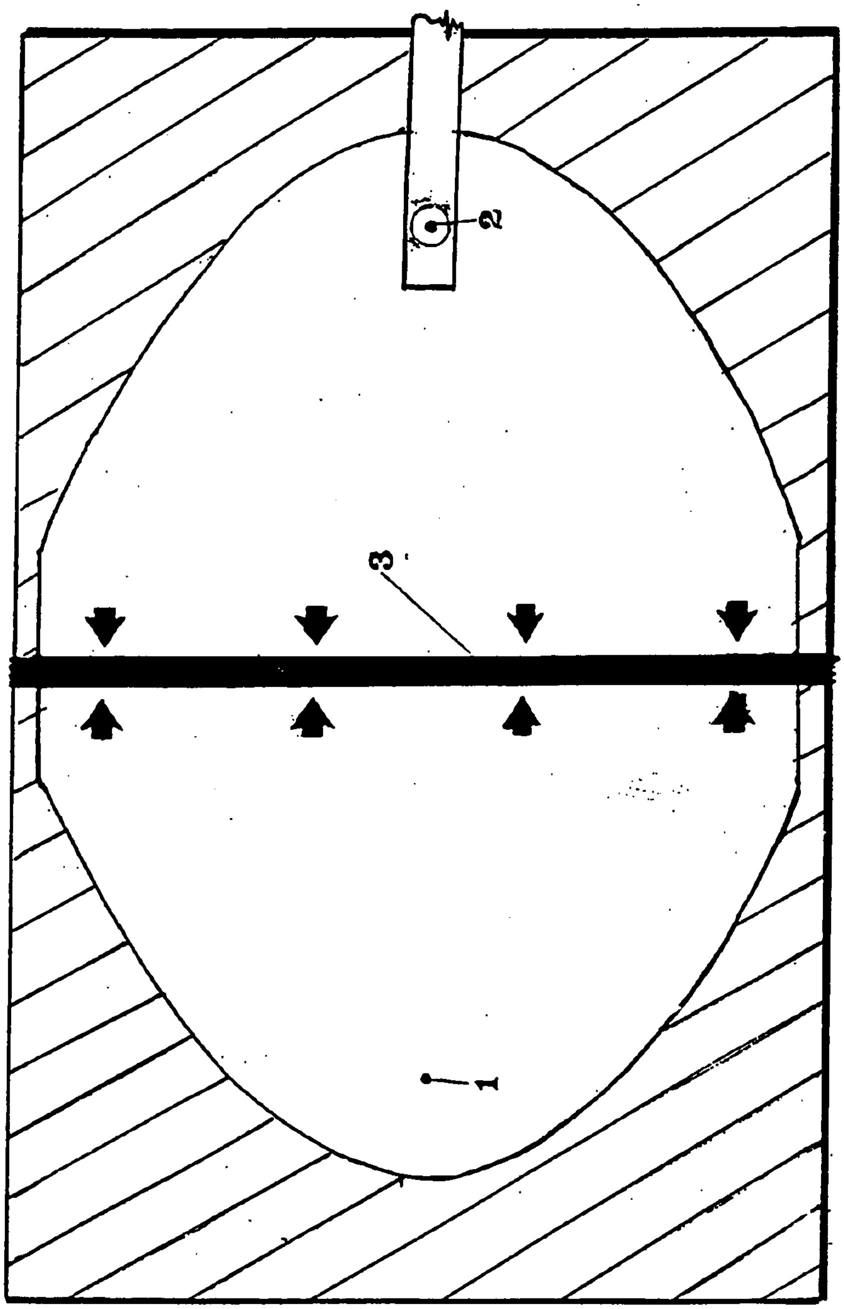


FIG. 6

SUBSTITUTE SHEET (RULE 26)

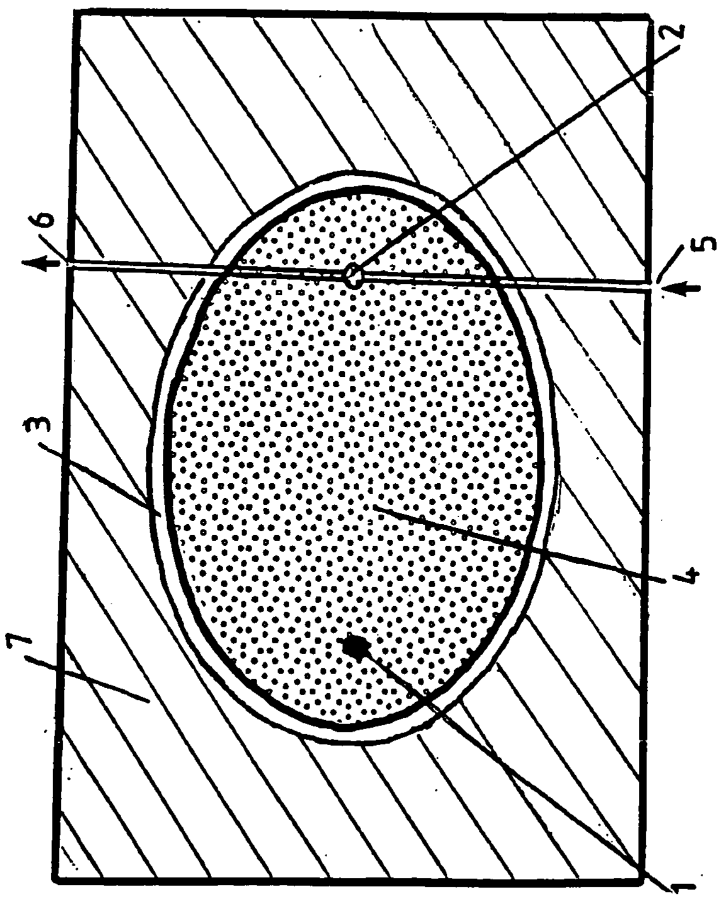


FIG. 7

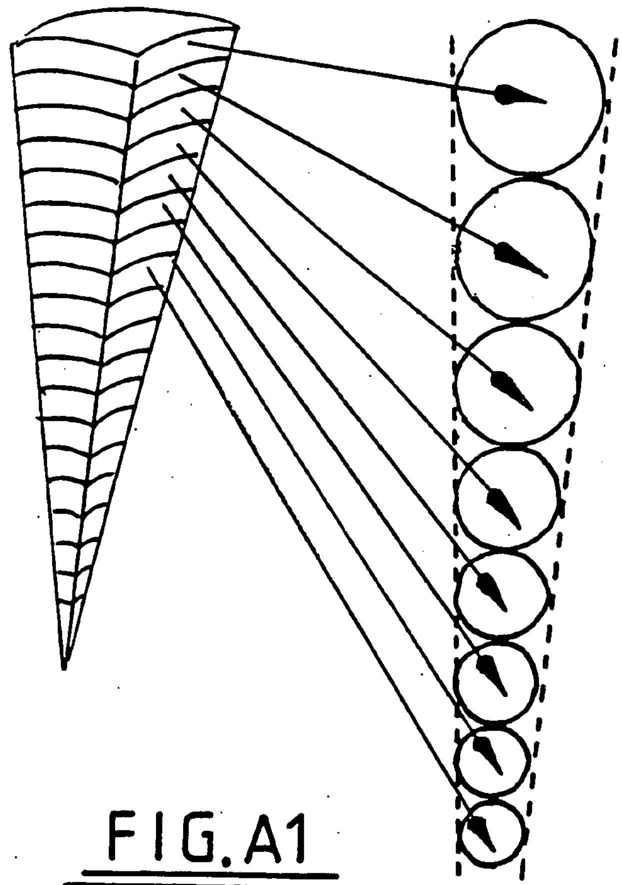
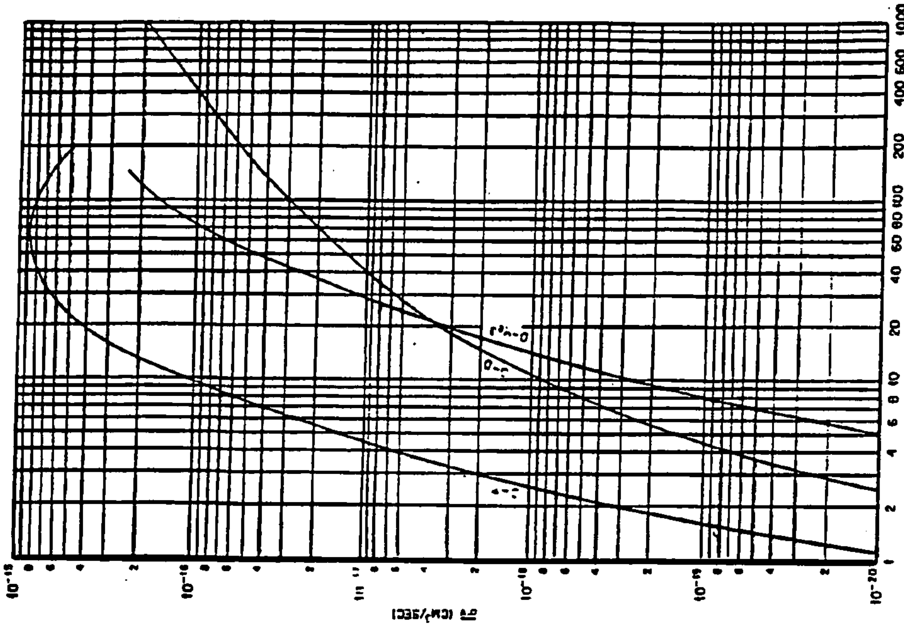


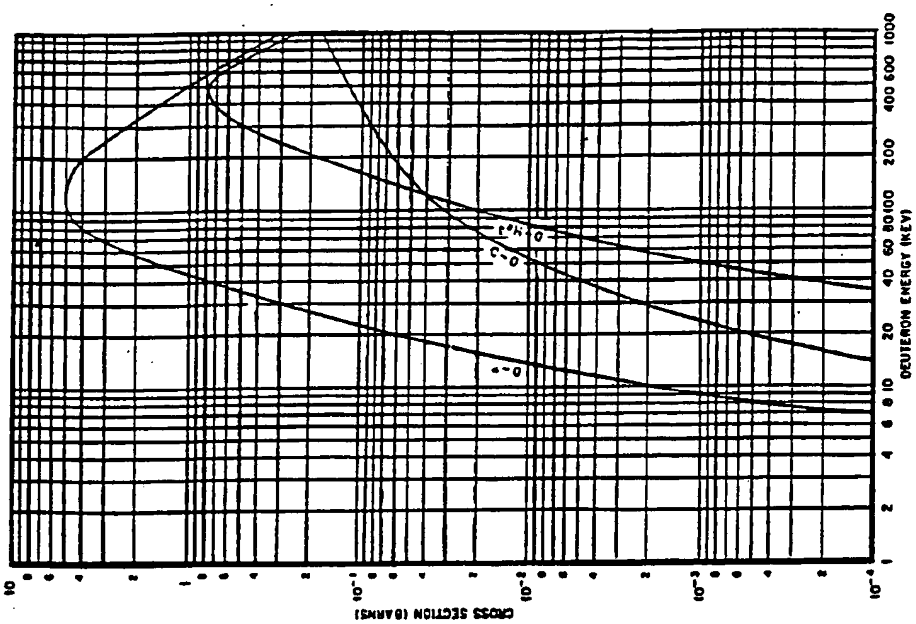
FIG.A1

SUBSTITUTE SHEET (RULE 26)



Values of $\overline{\sigma v}$ based on Maxwellian distribution for D-T, D-D (total), and D-He³ reactions.

FIG.B2 (after ref.B1)



Cross sections for D-T, D-D (total), and D-He³ reactions.

FIG.B1 (after ref.B1)

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 96/01187

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G21B1/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G21B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	DE,A,14 14 759 (U.DIEBNER) 3 October 1968	1,5,8,9, 12,33, 60,63,64
	see figure	
A	see page 2, paragraph 2 - paragraph 5	16-18, 29, 37-39,66
	see page 3, last paragraph - page 5, paragraph 1	

P,Y	WO,A,95 23413 (UNIV CALIFORNIA) 31 August 1995	1,5,8,9, 12,33, 60,63,64
	see page 3, line 6 - line 36	

	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

1

Date of the actual completion of the international search	Date of mailing of the international search report
5 September 1996	27.09.96

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax (+31-70) 340-3016	Capostagno, E

Form PCT/ISA/210 (second sheet) (July 1992)

International Application No
PCT/GB 96/01187

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO,A,91 13531 (UNIV MANCHESTER) 5 September 1991 cited in the application see page 2, paragraph 2 - page 3, paragraph 4 see page 5, paragraph 1 - page 6, paragraph 4 see figure 2	1,11,12, 28,29, 44, 46-48, 53,60
A	US,A,3 925 990 (GROSS ROBERT A) 16 December 1975 see column 1, line 56 - column 3, line 18	1,11,12, 29,59-61
A	US,A,5 122 506 (WANG XINGWU) 16 June 1992 see the whole document	51-54
A	DATABASE WPI Section Ch, Week 8519 Derwent Publications Ltd., London, GB; Class K05, AN 85-112992 XP002012673 & JP,A,60 054 200 (FUJIMURA A) , 28 March 1985	
A	EP,A,0 047 713 (PAPP INT INC) 17 March 1982	

1

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 96/01187

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
DE-A-1414759	03-10-68	NONE		
WO-A-9523413	31-08-95	NONE		
WO-A-9113531	05-09-91	AU-B-	7234591	18-09-91
		GB-A,B	2244592	04-12-91
US-A-3925990	16-12-75	NONE		
US-A-5122506	16-06-92	US-A-	4960760	02-10-90
		US-A-	5430009	04-07-95
		US-A-	5283234	01-02-94
EP-A-0047713	17-03-82	US-A-	4428193	31-01-84
		AU-B-	553762	24-07-86
		AU-B-	7640581	08-04-82
		CA-A-	1185707	16-04-85
		WO-A-	8200855	18-03-82